Report No. CG-D-24-96

Differential Beacon Receiver Testing

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FINAL REPORT
June 1996

Prepared for:

U.S. Department of Transportation
United States Coast Guard
Office of Research and Development
Washington, DC 20593-0001

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Technical Report Documentation Page

1. Report No. CG-D-24-96	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Differential Beacon Receiver Testing		5. Report Date June 1996
		6. Performing Organization Code
7. Author(s) Joseph W. Spalding, Mark T. Lunday, Marylouise K. Dowd		8. Performing Organization Report No. R&DC 18/96
9. Performing Organization Name and Address U.S. Coast Guard Research and Development Center 1082 Shennecossett Road Groton, Connecticut 06340-6096		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
		13. Type of Report and Period Covered Final Report
12. Sponsoring Agency Name and Address Department of Transportation U.S. Coast Guard Office of Research and Development Washington, D.C. 20593-0001		14. Sponsoring Agency Code Commandant (G-OPN) USCG Headquarters Washington, D.C. 20593-0001

15. Supplementary Notes

The R&DC technical point of contact is Jay Spalding, 860-441-2687.

16. Abstract

The Coast Guard's research and development of the Differential Global Positioning System (DGPS) led to the creation of a new type of radionavigation equipment, the differential beacon receiver. This device receives the digital broadcast of DGPS corrections over the marine beacon band (285-325 kHz). Its sole purpose is to provide the DGPS corrections to a properly configured GPS receiver which then applies those corrections in its navigation process to yield position accuracy of 2-10 meters. In order to conclude the research effort, the USCG Research and Development (R&D) Center conducted a campaign of testing to validate the methods being used in the Coast Guard DGPS service.

The performance testing, conducted at the USCG R&D Center in Groton, CT, tested the receiver's abilities under actual atmospheric and man-made interference. Performance was analyzed, with results measured in bit error rate, position accuracy and susceptibility to interference.

Coast Guard DGPS broadcast methods were evaluated and found to be sufficient for broadcast of the DGPS corrections. The results also led to the recommendation to change all DGPS broadcasts to 200 bits per second. The benefits of this change would be improved performance for the users of the system and simplification of the system as all beacon broadcasts would be at the same rate.

17. Key Words DGPS, Differential GPS, Radiobeacon, Minimum Shift Keying, MSK, USCG DGPS, RTCM SC-104	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. SECURITY CLASSIF. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

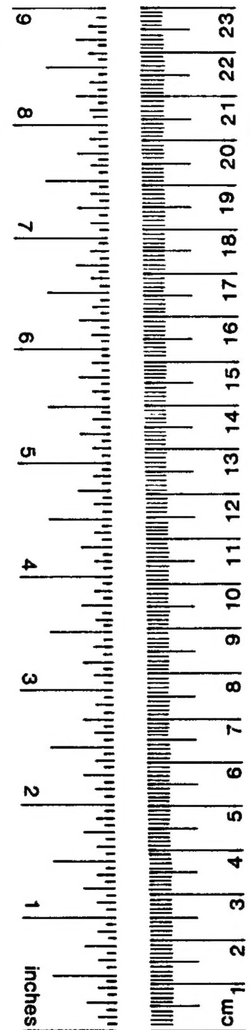
Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

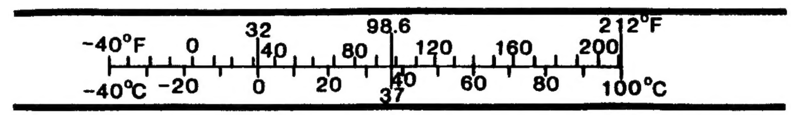
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



EXECUTIVE SUMMARY

The Coast Guard's research and development of the differential Global Positioning System (DGPS) led to the creation of a new type of radionavigation equipment, the differential beacon receiver. This device receives the digital broadcast of DGPS corrections over the marine beacon band (285-325 kHz). Its sole purpose is to provide the DGPS corrections to a properly configured GPS receiver which then applies those corrections in its navigation process to yield position accuracy of 2-10 meters. While fostering this new industry, the USCG Research and Development Center gained significant expertise, several receivers, and test equipment as successive generations of prototype and production equipment were developed. In order to conclude the research effort, the R&D Center conducted a campaign of testing to validate the methods published in USCG COMDTINST M16577.1 *Broadcast Standard For The USCG DGPS Navigation Service*. An additional investigation into receiver susceptibility to interference was conducted.

The performance testing, conducted at the USCG Research and Development (R&D) Center in Groton, CT, was done in three phases using four receivers from different manufacturers. In the first phase, the receivers were tested under actual atmospheric noise conditions. In the second phase of testing, DGPS corrections were received to determine throughput and navigation accuracy as a function of correction latency. This information was then used to determine optimal message type for different data transmission rates. In the third phase, the receivers were tested in the presence of a controlled interference source. Performance was analyzed for each of the phases, with results measured in bit error rate, position accuracy and susceptibility to interference.

Testing was conducted over several months to capture a variety of real atmospheric noise events. October 20, 1994 was chosen for presentation in this report as a storm front moved through the area producing natural burst noise interference to the DGPS broadcast. The results of this day should be considered as a 'typical bad day' for data transmissions in the marine beacon band. Bit error rate at 100 BPS was found to be about 20% lower than at 200 BPS. While the slower rate enjoyed a lower error probability, the faster rate was able to get a significantly higher volume of intact data to the beacon receiver. The data was then evaluated for the effect of the different broadcast options on navigation accuracy. RTCM SC104 Type 9-3 was found to be superior to RTCM SC104 Type 1 messages at both 100 BPS and 200 BPS due to the ability of the shorter message lengths to fit in between noise bursts typically found in the marine beacon band. Similarly, 200 BPS was found to be superior to 100 BPS as the messages took half the time.

The objectives of the test effort were met. Coast Guard DGPS broadcast methods were evaluated and found to be sufficient for broadcast of the DGPS corrections. We recommend that an additional test be conducted to verify the superior performance of 200 BPS broadcasts using actual high power DGPS transmissions. Given a positive result, we then recommend changing all Coast Guard transmissions to 200 BPS. The benefits of this change would be improved performance for the users of the system and simplification of the system as all beacon broadcasts would be at the same rate. All of the receivers were found to be susceptible to the intentional interference generated. Further research into interference should focus on a study of what typical man-made interference exists in major ports and evaluate the receiver's ability to deal with it.

Table of Contents

LIST OF FIGURES

ABBREVIATIONS

BEM	bit errors per minute
BER	bit error rate
BPM	bits per minute
BPS	bits per second
CPU	central processing unit
dbm	decibel millivolts
DGPS	differential Global Positioning System
DOD	Department of Defense
DRMS	distance root-mean-squared
FIM	field intensity meter
FRP	Federal Radionavigation Plan
FSK	frequency shift keying
GMT	greenwich mean time
GPS	Global Positioning System
kHz	kilohertz
LORAN-C	Long-range Radio Aid to Navigation, version C
MBB	marine beacon band
MER	message error rate
MSK	minimum shift keying
OPA-90	Oil Pollution Control Act of 1990
PPS	precise positioning service
R&D	research and development
RTCM SC-104	Radio Technical Commission for Maritime Services Special Committee 104
S/A	selective availability
SNR	signal-to-noise ratio
SPS	standard positioning service
SS	signal strength
USCG	United States Coast Guard
WER	word error rate

INTRODUCTION

From 1989-1994 the Coast Guard R&D Center conducted a vigorous program of development in differential beacon receivers. These receivers are intended for the receipt of differential GPS corrections being broadcast on medium frequency (283kHz-325kHz) marine band radiobeacons using MSK modulation. The R&D Center pioneered this medium for the purposes of differential GPS through several contracts and informal cooperative working arrangements with the companies interested in developing the technology. We basically had an open invitation to any companies desiring to test their beacon receiver developments at our site. At the time, most manufacturers were not within reception distance of a prototype beacon broadcast. In the process of the development, several evaluation units were acquired for USCG test and evaluation. This evaluation was initially of the different technological approaches being tried with this equipment. It was difficult to perform a meaningful comparative evaluation as the subject equipment, both hardware and software, was changing so rapidly within the industry. In April 1993, the Coast Guard Office of Safety, Navigation and Waterway Services published USCG COMDTINST M16577.1 *Broadcast Standard For The USCG DGPS Navigation Service*. This document contained the marine band radiobeacon broadcast parameters for the USCG DGPS service. With this document, we were able to formulate a meaningful test plan to validate these parameters using equipment representative of what was commonly available from the industry.

The report is broken into BACKGROUND, OBJECTIVE, EXPERIMENTAL PROCEDURES, TEST PLAN, EQUIPMENT, RESULTS, CONCLUSIONS and RECOMMENDATIONS sections. The BACKGROUND on this research is presented in a heirachical viewpoint from GPS to differential GPS and then DGPS utilizing marine beacons. EXPERIMENTAL PROCEDURES gives the overall philosophy of the tests conducted. The TEST PLAN presents the three sets of tests that were performed, giving the purpose and structure of each test. EQUIPMENT gives the technical details of the various pieces of hardware and software used to execute the test plan. RESULTS gives the graphical and statistical findings of typical high atmospheric noise data. CONCLUSIONS summarizes these results and RECOMMENDATIONS gives suggested actions for the Coast Guard to take based on this work.

BACKGROUND

Overview of GPS and DGPS

The Global Positioning System (GPS) is a navigational service that delivers all-weather, continuous, accurate navigation information on all points of the globe, with a 99.9% availability rate.[1] The GPS system, administered and maintained by the U.S. Department of Defense, provides two navigation services for GPS users. The Precise Positioning Service (PPS) which provides accuracies to 17.8 meters 2 drms (2 distance root mean square, approximately 95%), and is available only to DOD users. The Standard Positioning Service (SPS), available to civilian users, provides position accuracies of 30 meters or better (2drms), except when the selective availability (S/A) feature is enabled; then, SPS accuracies degrade to 100 meters (2drms).[1]

The differential Global Positioning System (DGPS) is a technology that can correct errors due to S/A and natural sources. DGPS uses a special GPS receiver, known as a reference station, placed

at a geodetically surveyed point to measure the range errors to each individual satellite. The error measurements are processed into corrections and formatted for broadcast. This broadcast is made with transmissions in the marine beacon band (MBB) (285-325 kHz)[1], to the user's differential beacon receiver. The user's GPS receiver is connected to the beacon receiver and applies the corrections in forming its position calculation. The result is an extremely accurate position determination which is typically on the order of a few meters when the user is within the nominal range of the DGPS broadcast signal.

<u>The Coast Guard's Role in DGPS Development</u>

The Coast Guard is charged under 14 U.S. Code 81 with the establishment, maintenance, and operation of electronic aids to navigation in order to prevent disasters, collisions, and wrecks of vessels and aircraft. The Coast Guard's role as a primary provider and user of radionavigation prompted the Coast Guard Research and Development program to begin GPS-related research in 1978. In the first stage of this effort, the goal was to characterize the stability and accuracy of the early prototype satellite broadcasts available to GPS users. As the task progressed, the R&D program applied principles developed in previous research using LORAN-C, and produced the first demonstration of Differential GPS. This demonstration was done using specially developed equipment for the R&D Center's research, and was completed in 1987. The research continued at the R&D Center, and in 1989 a prototype DGPS MSK broadcast was put on the air using the Coast Guard's marine radio beacon at Montauk Point, N.Y. The research program concluded that real-time DGPS corrections could significantly improve the accuracy, provide a high level of integrity, increase the usable coverage, and provide local control of the civilian portion of GPS without interfering with the military operation of the system. The research program also recommended that these improvements be incorporated into future navigational services utilizing GPS as a standard.[2]

In 1988, the Coast Guard's Office of Navigation and Waterways Safety at Coast Guard Headquarters selected DGPS as the tool to fill requirements for harbor and harbor approach navigation contained in the Federal Radionavigation Plan.[1] The Coast Guard developed an implementation plan that would establish a network of DGPS broadcast stations. Under the plan, the network would be operational in 1996, and would cover both coasts of the U.S., Hawaii, Alaska, and Puerto Rico. The format of the corrections would be based upon message and data standards developed by a multi-disciplinary committee under the sponsorship of the Radio Technical Commission for Maritime Services Special Committee 104 (RTCM SC-104). Additionally, the implementation plan followed the recommendations of the RTCM committee for signal modulation by selecting minimum-shift-keying (MSK); this ensured efficient use of the limited spectrum in the MBB.[3]

The decision to utilize the MBB for DGPS broadcasts greatly simplified implementation plans for a DGPS network; Coast Guard planners decided to utilize radio beacon transmitters already in place along the east and west coasts of the continental United States. This approach would reduce costs significantly, and would also shorten the time required to bring the DGPS network on-line. Since the Coast Guard already owned the property and the transmitters at the sites, all that was needed was a means of modulating the data for transmission.

MSK was originally proposed as the modulation method of choice for the MBB DGPS network, primarily due to the narrow bandwidth requirements in this frequency. Since MSK receivers were not available for the MBB, the Coast Guard R&D Center and Volpe National Transportation System Center (VNTSC) contracted with Racal Megapulse to produce two modulator and three receiver prototypes. Despite successful initial tests in 1989 at the R&D Center utilizing the MBB radiobeacon at Montauk Point, NY, manufacturers of electronic navigational equipment were wary of producing MSK receivers for DGPS corrections. There was no source of MSK transmissions in the MBB for use by the mariner or any definite plans for an established service. In 1990, the Coast Guard R&D Center took the lead in the field and set up full time MSK transmissions from the radio beacon at Montauk Point, NY. Using the transmitter and antenna at the radio beacon site along with a prototype MSK modulator, DGPS corrections were transmitted at a data rate of 50 bits-per-second (BPS). After initial test and evaluation, the DGPS broadcast from Montauk Point became the first MBB MSK DGPS broadcast in the world on August 15, 1990.

The RTCM SC-104 recommendations for differential GPS originally recommended that MBB DGPS be composed of MSK data corrections using RTCM message format Type 1 at 50 bits-per-second (BPS)[4]. Additional parameters were available for the network, such as bit rates of 25, 100 and 200 BPS, and a shorter RTCM message format, Type 9. In 1993, the Coast Guard utilized these other parameters in its Broadcast Standard; all corrections would now be at either 100 or 200 BPS. Also, the correction formats for the final network were all changed to RTCM message Type 9. Both of these changes were done in order to make the signals more resistant to atmospheric interference.

However, concerns existed over the ability of commercial MSK beacon receivers, already in production by several companies, to perform adequately under the new parameters. Although the alternate parameters were always available, the switch from Type 1 to Type 9 and the increase in speed to 100 BPS (or 200 BPS at some sites) was not originally envisioned as a permanent change. Since the specifications had now been permanently modified, the Coast Guard was interested in the performance characteristics of the commercial MSK beacon receivers relative to the proposed DGPS service parameters. This desire for validation of the broadcast parameters focused the MSK beacon receiver testing, enabling its conclusion with this report. The results of the tests would be used to validate the capabilities of the receivers, and to experimentally determine performance for the RTCM message types at 100 and 200 BPS data rates.

OBJECTIVE

The objective of this test effort was to determine the performance characteristics of several state-of-the-art DGPS MSK beacon receivers under varying conditions. Specifically, the focus of testing would be on how the receivers performed in the presence of atmospheric noise and other continuous wave (CW) carrier interference in the MBB spectrum. The results of this test would be used to evaluate the expected performance of the Coast Guard DGPS service in the presence of interfering noise sources.

EXPERIMENTAL PROCEDURES

The philosophy and design of the test are presented in this section. Variables are accounted for, the test facility is generally described, calibration procedures are given, and data collection and analysis routines are presented to give the reader the background required to understand the results of the tests.

Variables

There are a number of variables involved with any test that incorporates the transmission and reception of radio signals. Obviously, the goal is to limit and control all variables that impact upon the test setup. By fixing these inputs to known values, reliable and precise results can be obtained from the tests. This allows for accurate comparisons and conclusions about receiver performance. The input variables in this setup can be subdivided into two categories: controlled inputs, and partially controlled or non-controlled inputs.

The controlled variables that were considered for this test included the MSK signal bit rate, the signal frequency, the signal transmitted power, and the RTCM message content. In order to conduct the tests, all but one of these inputs were preselected. The one adjustable input was the MSK signal data rate.

The partially controlled or uncontrolled inputs could not be entirely removed from or set to fixed values in the experiment. Inputs of this type included: static noise from man-made sources, other carriers in the MBB that interfered with the testing of the controlled MSK signal and atmospheric noise. Every effort was made to reduce the effect of the first two of these inputs. The receivers were placed at an electrically quiet location. A frequency in the MBB was chosen that was not close to any strong interfering signals. Additionally, the selection of a remote location of the receivers completely eliminated several interfering signals and noise sources that were present at the R&D Center main building. Atmospheric noise was not controllable so testing was carried out on many days in order to get an adequate sampling of varying amounts of noise. Also, the magnitude of the noise relative to the signals being transmitted was assumed to be equal across the population of receivers during simultaneous testing of the receivers.

Test Facility

Due to the rapid development and relatively recent emergence of DGPS as a navigational technology, there have been few detailed studies that measured receiver characteristics in the presence of noise and signal interference. Performing such tests is not a trivial task, since a signal testing facility is required. While several DGPS beacons are currently transmitting corrections as part of the prototype system, control of the signal required for testing purposes is difficult to obtain. Many of the transmitter sites are remotely located; additionally, a method of generating signals whose content is known in advance precludes the use of these prototype transmissions, since they are transmitting real-time correction data.

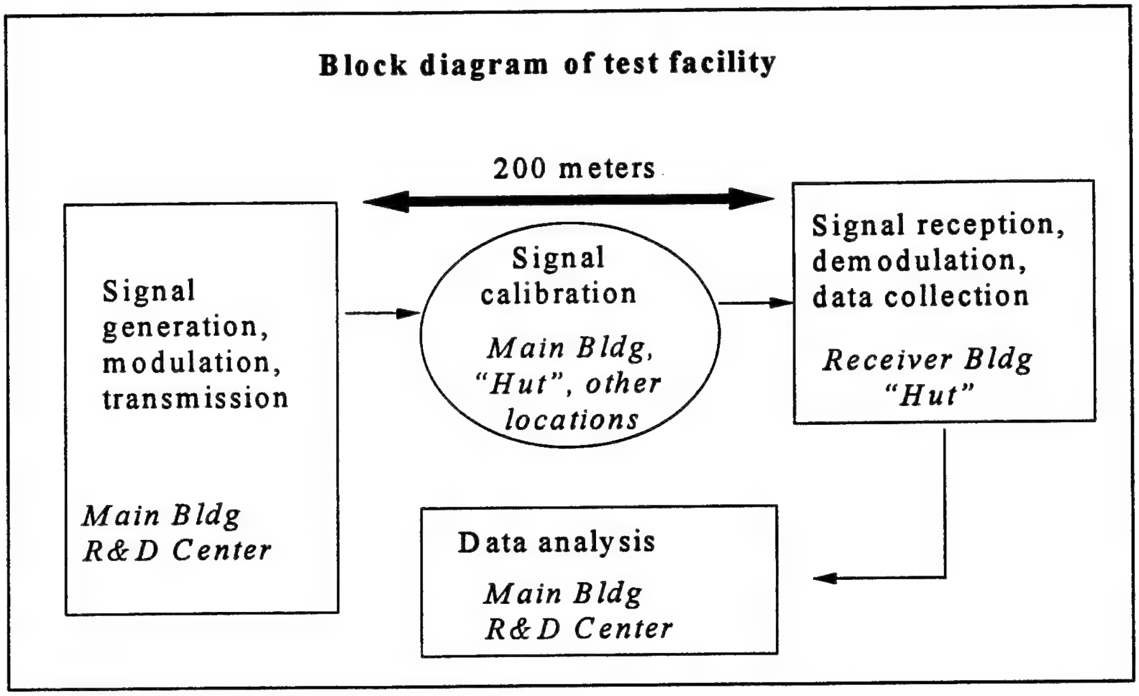


Figure 1 Block Diagram of Test Facility

Due to the difficulties with performing such tests and the need to validate USCG DGPS broadcast parameters, the Coast Guard R&D Center utilized existing equipment to establish a testing range. Figure 1 shows a block diagram of the range setup. The procedure for signal testing is straightforward; the actual implementation was much more difficult, and is discussed in the **EQUIPMENT** section.

The procedure, shown in the block diagram, can be described as a series of steps. First, a known and repetitive binary stream of DGPS corrections is generated in RTCM SC-104 format. The data is then sent to an MSK modulator, which generates an MSK signal on a selected frequency in the MBB. The signal is transmitted, then received at a remote location 200 meters from the transmitter antenna. The receivers detect the MSK signal and demodulate the RTCM corrections. The correction data is collected and stored at the remote location and then brought back and analyzed at the main building.

Signal Calibration

Signal calibration is a critical part of the test setup. The test conditions were adjusted to simulate MSK signal reception at the fringe of beacon coverage. Coast Guard MBB radio beacons have adjustable power output levels; each beacon is set up to provide a specific coverage range over seawater. The beacon coverage is defined by the signal's field strength, in microvolts per meter, at a specified distance, in nautical miles (NM). Coast Guard MBB DGPS radio beacons are rated at one of two field strength levels: 75 or 100 microvolts per meter. The Montauk Point, NY radio beacon, for example, has a specified signal field strength of 75 microvolts per meter at a

distance of 130 NM. A logical test location for receiver performance would be at the edge of a radio beacon's coverage. This condition would put the receivers in a worst-case scenario condition; the position of the user would be at the maximum rated range of the beacon. The value of 75 microvolts per meter was chosen, since it is the more common and lower of the two field strength values. The locally transmitted signal would then have to be calibrated so that the strength of the signal at the receiving site was 75 microvolts per meter.

Signal Generation, Reception, and Correlation

For the tests in this experiment, a repetitive loop of RTCM DGPS corrections was required. Several requirements had to be met when the test RTCM corrections were created. The RTCM SC-104 format for DGPS corrections dictates that the last two parity bits of a message word (an RTCM word is comprised of 30 data bits) will be included in the parity calculation of the next message word. Also, the last bit of a message word determines the sense, or complement, of the next RTCM word's data bits. These requirements demand a valid continuity of the fixed RTCM data loop. Experimental tests on a 386 CPU computer were conducted until an acceptable and valid RTCM sequence was created with the proper word parameters. It was necessary to minimize the size of the fixed loop pattern in order to minimize the time needed to correlate the data streams in real-time. A loop size of one message containing four RTCM 30 bit words was selected as the optimum pattern.

The MSKTest software correlated the known fixed RTCM data pattern to the data stream received by the differential beacon receiver. Correlation was done by shifting the known data pattern loop and performing bit comparisons (exclusive OR) between the known pattern and the received data bits. The number of correct comparison matches was accumulated for each shift of the known bit pattern. This shifting and comparing continues until a high percentage of bit matches is detected. The percentage value for the threshold was experimentally determined to be 66 percent.

Once this percentage threshold was exceeded, the MSKTest program presumed that the two data streams were correlated. Then, the software began to collect statistics on the number of incorrectly received bits by the receiver. A history of the number of incorrect bits was maintained by the program in order to perform a real-time check for any possible shifts between the data streams. This bit shift detection scheme would detect a loss in correlation if the number of incorrect bits exceed a certain threshold. The program examined the previous thirty bits. If ten or more bits did not correlate, then the program presumed that correlation had been lost. In this case, the correlation operation was performed again in order to reacquire data synchronization.

Statistics on the receiver data output were collected in a log file, and included the total number of bits received and incorrect bits. In addition, the log file contained totals for received RTCM words and RTCM messages, along with receiver performance statistics. Bit error event data were stored in a bit error file. This file contained the date, time, and location in the message of every bit error occurrence. These two data files provided sufficient information to allow post-processing and analysis of receiver performance.

Data Collection and Analysis

Statistics on the receiver's interpretation of the incoming data were collected in a log file. Raw data in the file included the total number of bits elapsed and the total number of incorrectly interpreted bits. In addition, the log file contained totals for RTCM words and RTCM messages. Day of year and time of day were part of every entry in the file record. Signal strength (SS) and signal-to-noise ratio (SNR) were also included in every record entry. Entries in the log file were recorded at preset time intervals (usually once a minute). It was therefore possible to determine statistics about the data between any period of time down to the resolution of the recorded time interval. Event data such as bit errors were stored in a file called a bit error file (BEF). This file contained the date, time, and location in the message of every bit error occurrence. In addition, the value of the shifting required to correlate the incoming signal to the known, repetitive loop was appended to each bit error entry.

Transmitting Antenna Design

Antenna design for this testing presented a number of unique challenges. The final antenna design for the first and second tests was a ten-turn rectangular loop, with dimensions of 4' x 16' mounted on the R&D Center roof, orientated in the y-z plane, with the antenna plane orthogonal to the receiving site. Due to the high standing-wave-ratio (SWR) of this design, input power was kept to a minimum; in spite of this, there was sufficient signal strength at the receiving hut to replicate the desired MSK beacon signal strength.

For the final tests, antenna modification was required. A much stronger signal was needed at the receiving site. A traveling wave antenna design by Balanis[5], approximately 250 feet in length, served as a much more efficient radiator. Typical SWR values were 3:1, and for a forward power of 5 watts, the reflected power was only 2 watts.

Signal Receiving Site

Due to the electromagnetic noise at the R&D Center (from computers and other electrical equipment), a remote location was selected for receiver placement. At this location, an enclosed housing made of fiberglass and measuring 20'x10'x10' was utilized to store the receivers. The building had 120VAC power, and air-conditioning/heating for climate control. To further reduce non-atmospheric noise at the receiver location, laptop computers with LCD screens were selected to record data and control the receivers; linear DC power supplies for the equipment were incorporated; and incandescent lighting was used instead of fluorescent lighting. The result was a receiving location that had a noise floor 30 dBm lower than the main R&D Center building.

The differential beacon receiver whip antennas and their respective couplers were mounted on the top of the fiberglass enclosure. Each antenna was attached to the top of a vertically mounted piece of four foot long one inch diameter galvanized iron pipe. Each antenna was kept at least three feet apart from the others. Whip antennas were selected for use during the testing in order to permit equitable performance comparisons among the units.

TEST PLAN

The R&D Center purchased six different commercial off-the-shelf (COTS) differential beacon receiver models. These receivers represented a range of features, capabilities, and demodulation techniques.

While the R&D Center was originally comparing the capabilities of all of the receivers under the modified broadcast parameters, the final testing plan placed greater emphasis on performance determinations against an ideal receiver that was impervious to all interference and noise. The test setup was limited to eight data collection computers, allowing just four pairs of receivers to be tested. Two of the receivers had to be dropped from the test. The units were eliminated as follows: One unit did not have the capability to receive data at 200 BPS, and could not be used in the evaluation of both bit rates. Another unit that was no longer in production was also dropped from the testing. The tests proceeded with pairs of the four receivers.

There were three main areas of interest for the experiment. The first area was the ability of a receiver to detect signals at significant distances from the transmitter site in the presence of atmospheric noise and quantify this as bit error rate. The second area was to measure the navigation performance as a function of message throughput given varying amounts of atmospheric noise. The third area of interest was the vulnerability of differential beacon receivers to man-made signal interference, either from unintentional carrier interference or intentional DGPS broadcast signal jamming efforts.

Bit Error Rate (BER)

The purpose of the BER test was to determine receiver susceptibility to atmospheric noise. This test examined the effect of atmospheric noise on data throughput at the bit level, using bit error rates detected at the receivers. Signal reception was examined as differences between the four different receivers, and differences for any given receiver between receiving data at 100 BPS vs. 200 BPS. The receivers were tested by running two copies of the same model simultaneously: one at 100 BPS and one at 200 BPS. Although the MSK signals were at different speeds and frequencies, each receiver of the pair monitored the same RTCM DGPS correction data of the repetitive loop generated by the transmission facility. Data collection was performed on each receiver during this time, and bit errors were recorded for analysis and comparison. Specifically, the following information was collected and examined: the quantity of bit errors for each receiver during the test, and the number of bit errors for each minute for each receiver. The typical time period of data collection for these tests was 24 hours. From this data, a graph of bit errors each minute averaged over the last hour vs. time was created. The plot was derived by passing the bit errors for each minute through a low pass filter. The filter is a 60-sample averaging function with equal weights placed on each sample. This feature provided a smoother plot that allowed easier comparisons between different receivers. The low-pass filter aspect eliminated random, single event idiosyncrasies in the data, and instead indicated general performance trends.

Due to the real-world setting and the inability to control atmospheric noise, a shotgun approach to data collection was taken. Testing was conducted on approximately 40 days during the summer and fall of 1993 and 1994, representing more than 500 hours worth of data collection in order to achieve a broad spectrum of samples. From this large collection, six days were selected as representative of atmospheric conditions from relatively quiet to extremely noisy. Receiver signal-to-noise ratio (SNR) values were factored into the selection of the six days. Samples which had significant atmospheric noise were chosen for analysis.

Message Type - Navigation Accuracy (MTNA)

The purpose of the MTNA test was to examine the effect of realistic, strong non-gaussian atmospheric noise on the throughput of two message types (Type 1, Type 9-3) being broadcast at different speeds (100 BPS, 200 BPS). Analysis would then be performed to gain insight into the relationship between these variables and navigational accuracy. Previous calculations and field trials conducted by Enge[6] have shown that RTCM Type 9 messages, in spite of reduced data transmission efficiency and increased reference station complexity, have distinct advantages over Type 1 messages in the presence of atmospheric noise. The current USCG DGPS implementation plan calls for all transmissions to be done using RTCM Type 9-3 message formats.

First, data were collected using the R&D Center's Reference Station Monitor (RSM) software. This data indicated radial error as a function of average correction latency for both Type 1 and Type 9-3 messages. Two curves were developed: radial error as a function of age for Type 1 messages and radial error as a function of average age for Type 9-3 messages. With the data files collected in the BER test, an analysis was made regarding the ability of specific message types at certain speeds to "pass through" the noise during static impulse lulls, and thus reach the receiver. By post-processing the data and examining the time periods between bit losses, the age of the DGPS corrections was determined based on the various message lengths. Using these age values as inputs to the radial error versus age curves, derived from the RSM data collection, a 95% radial error figure was arrived at and plotted. Over a given period of time, comparisons between RTCM message types and MSK bit rates were made, and conclusions were drawn about the success of the different signal parameters under varying atmospheric noise conditions.

Interference/Jamming (INTJAM)

The purpose of the INTJAM test was to look at commercially available receiver technology in terms of susceptibility to man-made signal interference. This was done by broadcasting two MSK signals with the same data on different frequencies; one signal would be the control, and the other would suffer from intentional interference attempts, conducted by a controlled carrier wave. By collecting BER and RTCM 30 bit word error rate (WER) statistics in real time and comparing the data to information about the CW interference, conclusions were made regarding the susceptibility of differential beacon receivers to man-made interference.

For this test, two MSK signals were used; the first on 316.5 kHz, served as the victim of interference by the jammer. The second MSK signal, at 313.5 kHz, functioned as the control of the experiment. The jammer signal frequency and level were varied around the 316.5 kHz MSK signal.

EQUIPMENT

Figure 2 shows a schematic of the equipment used for this research. For the first and third tests, Bit Error Rate (BER) and Interference/Jamming (INTJAM), control of signal frequency, bit rate, and data content was required. This necessitated the creation of the repetitive loop of MSK data; this enabled actual bit error rates (BER) to be determined from the data output by the receiver. A loop size of one message containing four RTCM 30 bit words was selected as an optimum pattern. This equated to a loop size of 120 bits. The program that created the RS-232 data for this was written in Borland C, and was run on a Zenith model 184 8088 CPU laptop computer. The second test, Message

Throughput/Navigation Accuracy (MTNA), required the generation of real-time DGPS corrections. Ashtech Z-12 reference stations were used at the main R&D Center building to generate this data.

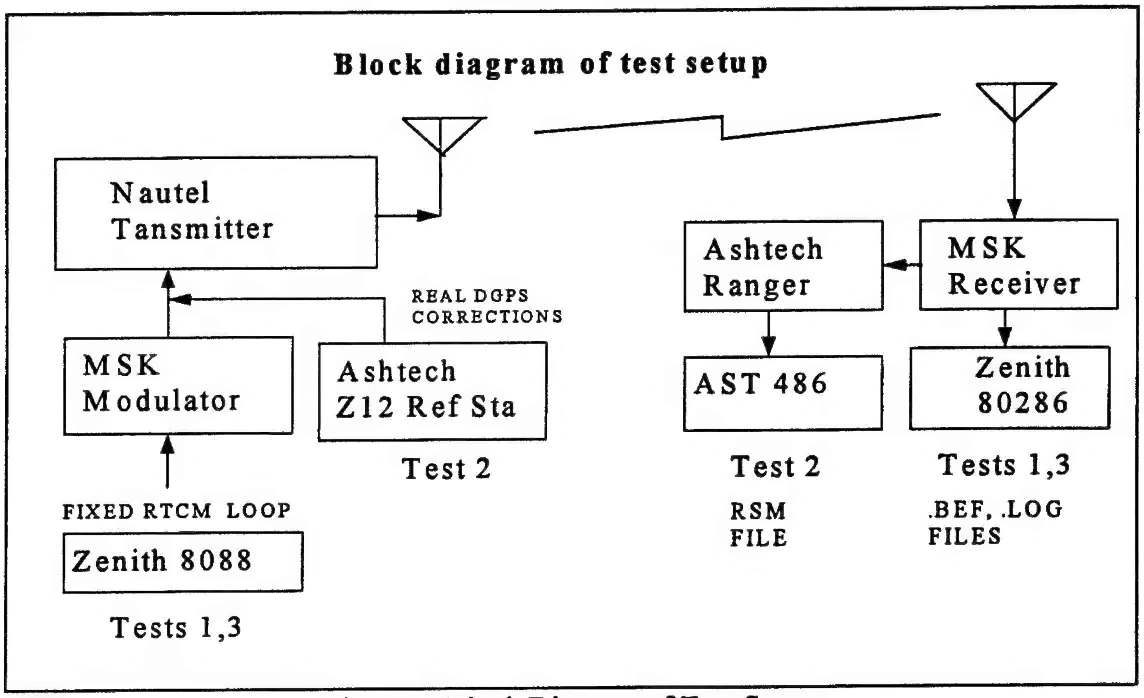


Figure 2 Block Diagram of Test Setup

MSK modulators that converted the RTCM data to MSK signals at the desired frequencies were used in all three tests. The modulator used in the first and third test was based upon a design originally created by the R&D Center in 1989, and used direct digital synthesis to create the MSK signal. For the second test, modulators within the Ashtech reference stations were used to generate the MSK signals.

The MSK signal was transmitted by using a Nautel Marine Beacon Band (MBB) radio beacon amplifier. It is a wide-band class A amplifier, with a maximum forward power of 100 watts. Although the Coast Guard generally uses 250 and 1000 watt amplifiers, the rest of the radio beacon unit is identical to the test unit.

As mentioned in the **EXPERIMENTAL PROCEDURES** section, the MSK signal used in the tests was adjusted to simulate reception at the fringe of beacon coverage. A Coast Guard field intensity meter (FIM) and an HP 3589A spectrum analyzer were used to take field strength measurements of Montauk Point at the receiving location. These values were used to adjust the output power of the local signal until the level on the spectrum analyzer corresponded to a FIM measurement of 75 microvolts per meter.

For the MTNA tests, real-time calculation of radial error was required. This necessitated a GPS receiver at the receiving site, on a surveyed antenna location that would allow navigation error calculations to be performed. An Ashtech Ranger (M-12) receiver was used for the navigation tests. A location was chosen on the roof of the receiving site building, and its position was surveyed using

Ashtech L-XII and Ashtech Z-12 geodetic GPS receivers and Ashtech Prism geodetic surveying software.

Data recording equipment at the receiving location included Zenith 80286 CPU laptops, in conjunction with software developed by the R&D Center. The software controled the differential beacon receivers and correlated the known fixed RTCM data pattern to the data stream received by the receivers.

For the MTNA testing, two Ashtech Z-12 reference stations were set up at the main R&D Center building with a common antenna. Two Ashtech Ranger receivers with a single surveyed antenna at the receiving site were installed. The program RSM was used to record the resulting DGPS positions and associated data in binary files. The program RSM_DATA was used to extract the DGPS correction age, position, and time stamps from the RSM file into a spreadsheet format. The position data, together with the known GPS antenna location, was used to reproduce the actual radial error for each data sample. This was correlated with the correction age information to empirically determine navigation error as a function of DGPS correction age. Tables of radial error versus message age for RTCM message Type 1 and Type 9-3 were created by using the analysis program MATLAB and a least-mean-squares matrix algorithm to interpolate and curve-fit the RSM data.

For the INTJAM tests, additional specialty equipment was required. A Hewlett-Packard HP-8904A frequency synthesizer was used to generate the CW interference signal. Specialized QuickBasic code was developed to control the HP-8904A and record signal levels in a log file.

RESULTS

Analysis was performed for several days of collected data. After confirming that the results from day to day were consistent, we chose a typical bad stormy day for more detailed analysis. October 20, 1994 was chosen as a severe storm front moved through the area causing a great deal of atmospheric burst noise in the form of static discharges (lightning). Results for this day are presented for the first two types of tests. Bit error rate is first presented in graphical form followed by Message Type Navigation Accuracy, and then Interference and Jamming results. It should be noted that data from the bit error test were also used in the computation of the results of the MTNA navigation errors. The bit error files from the bit error tests gave us a sequence of good bits versus bad bits for the various test periods. INTJAM test results are completely separate from the other two tests and were conducted on another day.

Bit Error Rate

The first step in the analysis was to graph and compare the average bit error rates for the 24 hour period of the test. These figures for October 20, 1994 (Julian day 292), are shown in Figure 3 through Figure 10 . The four receivers, designated 'A', 'C', 'E', and 'F', were each tested at 100 and 200 BPS. The figures show a discernible difference in performance between receivers, as well as between transmission rates.

The following eight figures illustrate the performance for this stormy day. An atmospheric noise event (or series of noise events) occurred over the time period of 0000 GMT to 0900 GMT, which corresponded to 1900 EST to 0400 EST. Another event occurred from 1300 GMT to 1500 GMT (0800 EST to 1000 EST.) This second event was much more benign in its effects on BER values, and

was of shorter duration than the first event. Finally all of the figures indicate a gradual BER increase occurring at the end of the testing period.

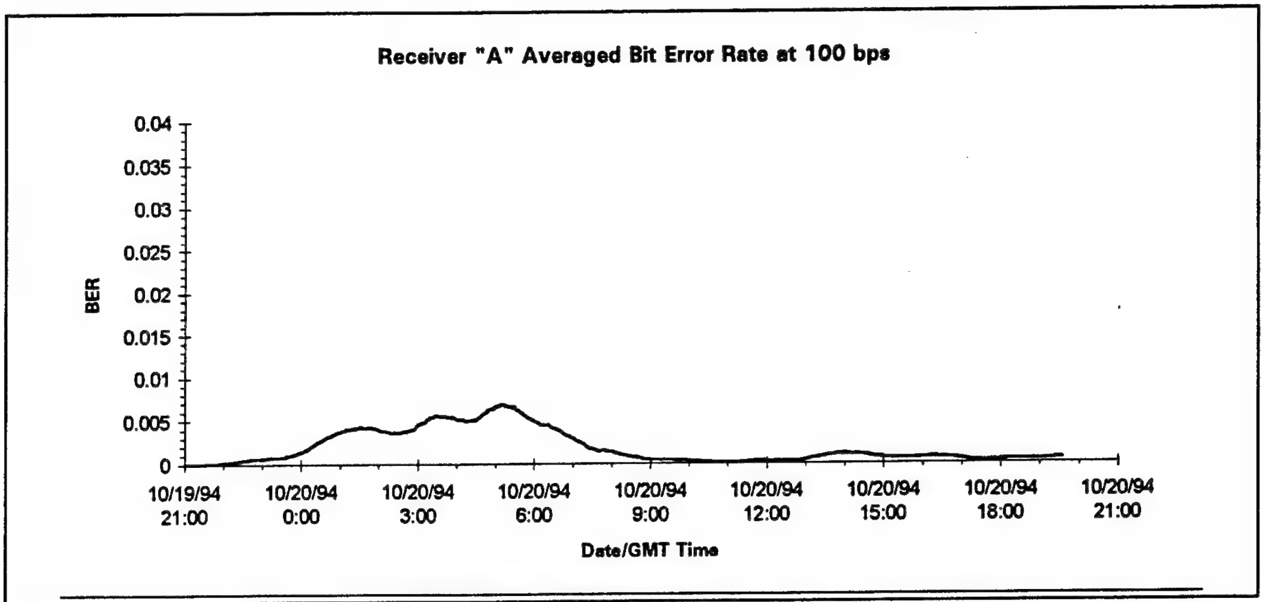


Figure 3 Receiver A Averaged Bit Error Rate at 100 BPS

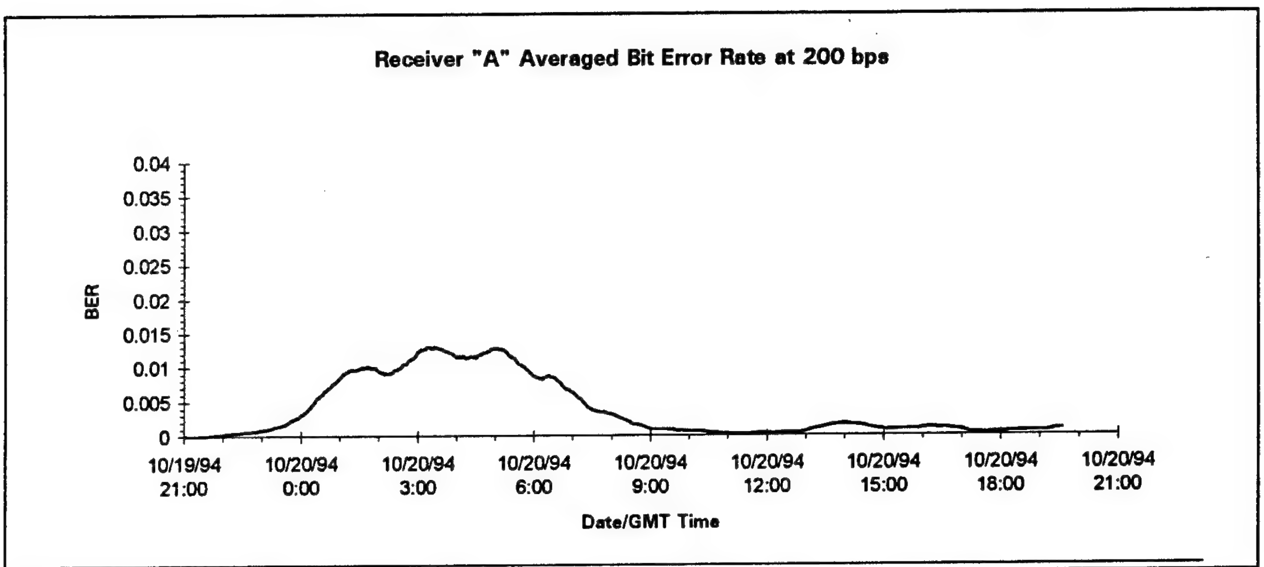


Figure 4 Receiver A Averaged Bit Error Rate at 200 BPS

The BER rise during the early part of the data set is attributable to thunderstorms along a front that moved through the area. The later slight increase is of uncertain origin, probably distant storms. Although the noise is believed to be caused by a front approaching the area, no specific data collection measurements were made regarding the frequency and intensity of burst noise in the MBB. However, general measurements on the spectrum analyzer indicated that burst noise was present on that day.

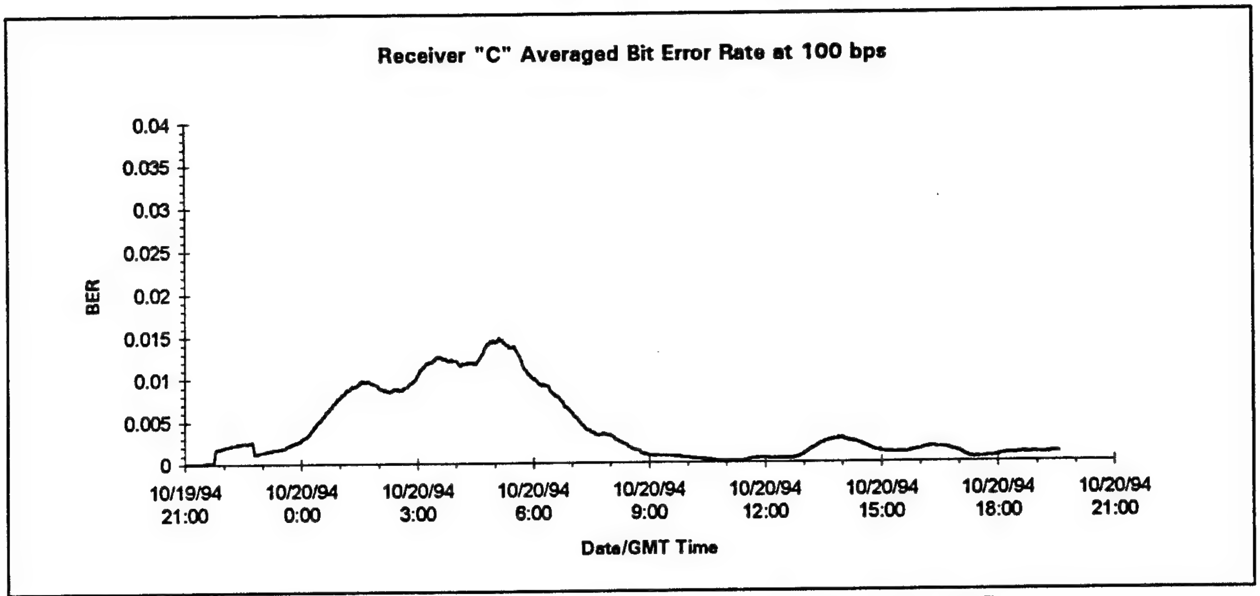


Figure 5 Receiver C Averaged Bit Error Rate at 100 BPS

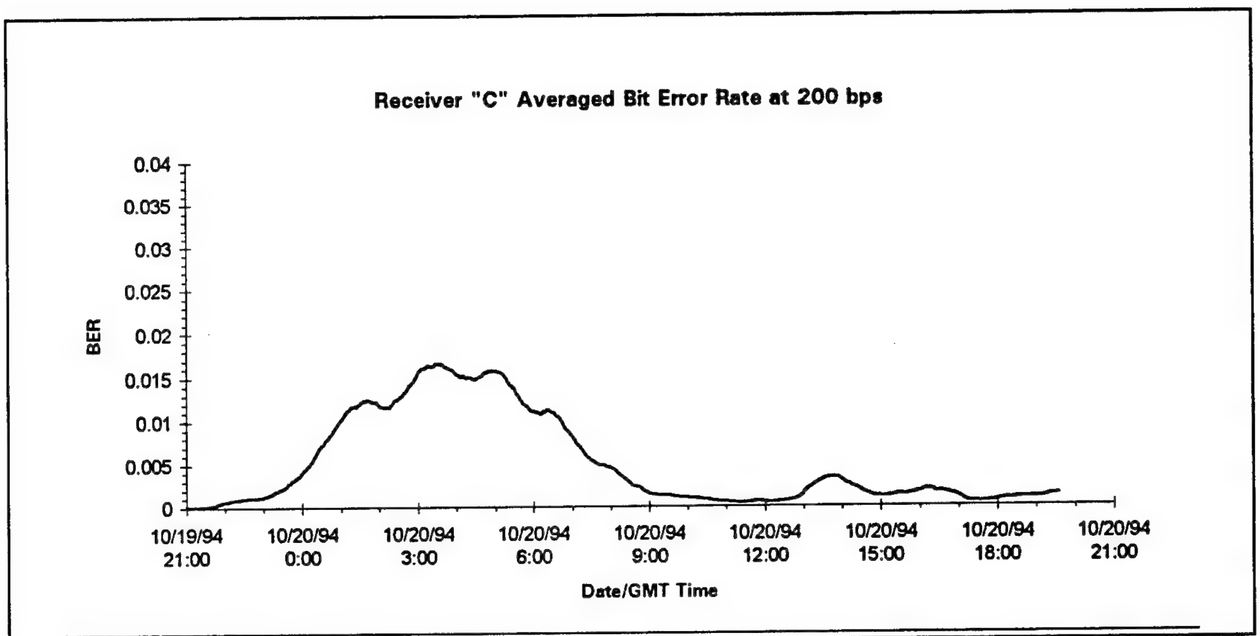


Figure 6 Receiver C Averaged Bit Error Rate at 200 BPS

In the case of all four receivers, the units operating at 100 BPS had lower BER values than the units operating at 200 BPS during the noise events. This is to be expected, with one half the energy going into each bit at 200 BPS it is more susceptible to noise. Note however, that the BER increase did not necessarily double, as might be expected in gaussian noise conditions. An individual noise spike of a duration shorter than 1/200 of a second will affect just a single bit at either 100 or 200 BPS.

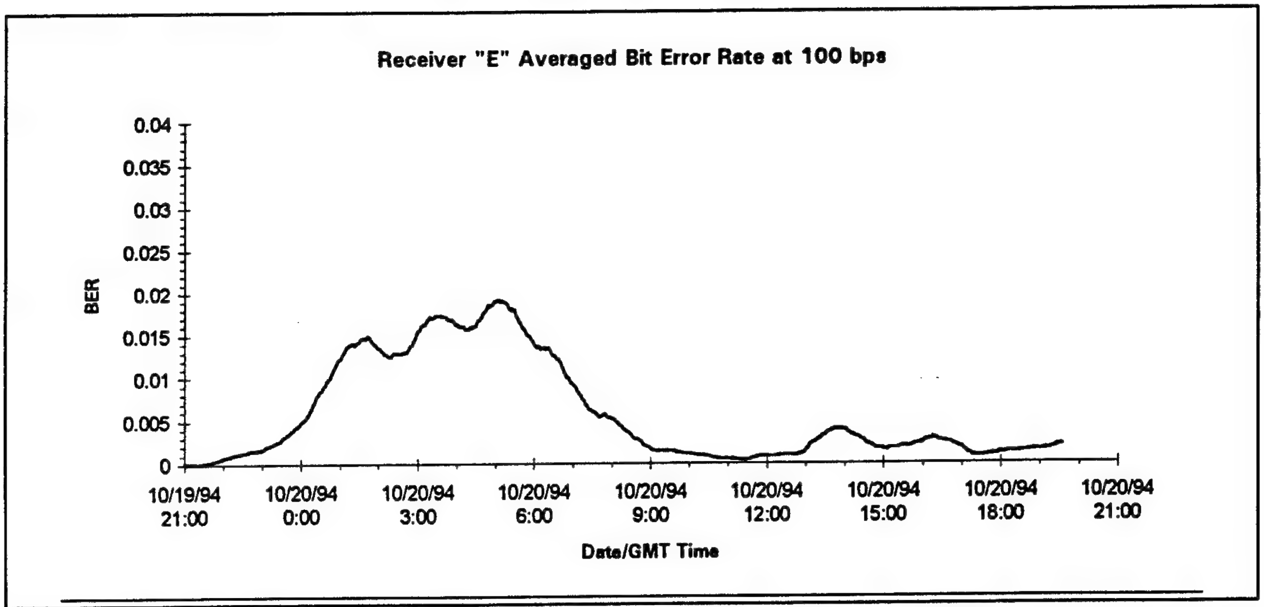


Figure 7 Receiver E Averaged Bit Error Rate at 100 BPS

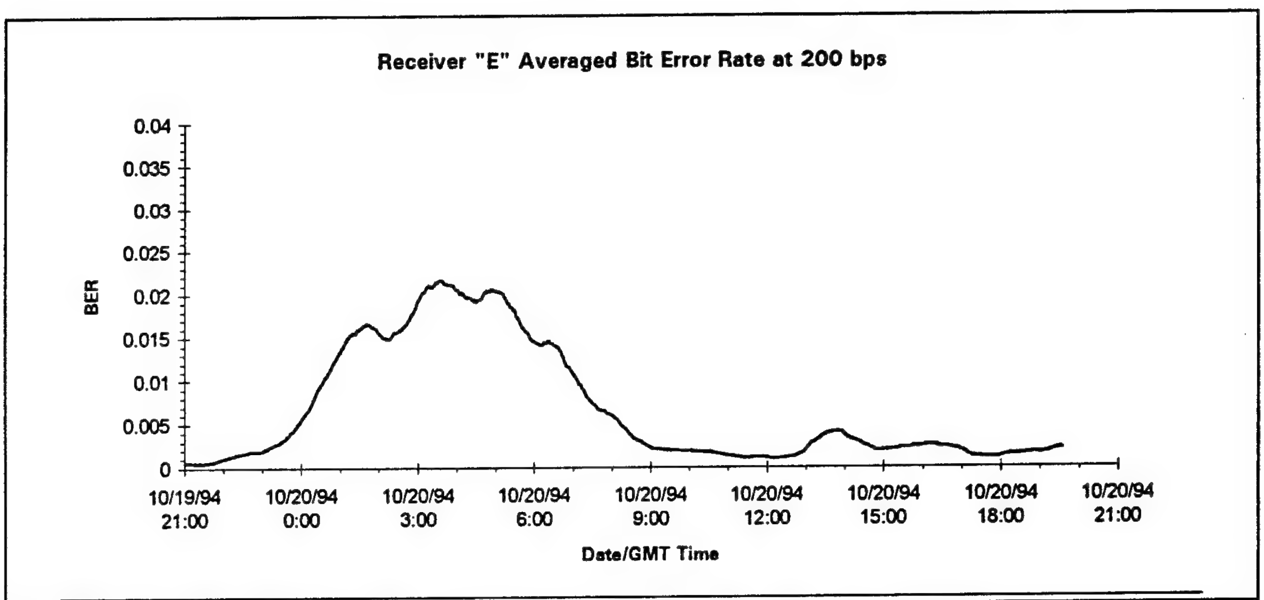


Figure 8 Receiver E Averaged Bit Error Rate at 200 BPS

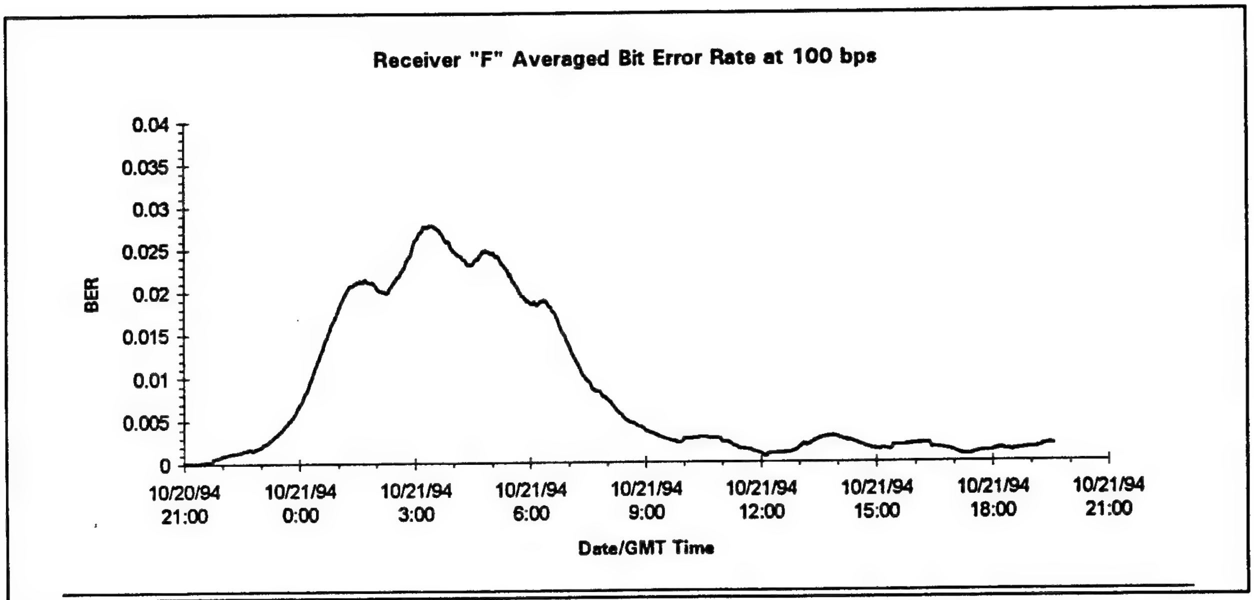


Figure 9 Receiver F Averaged Bit Error Rate at 100 BPS

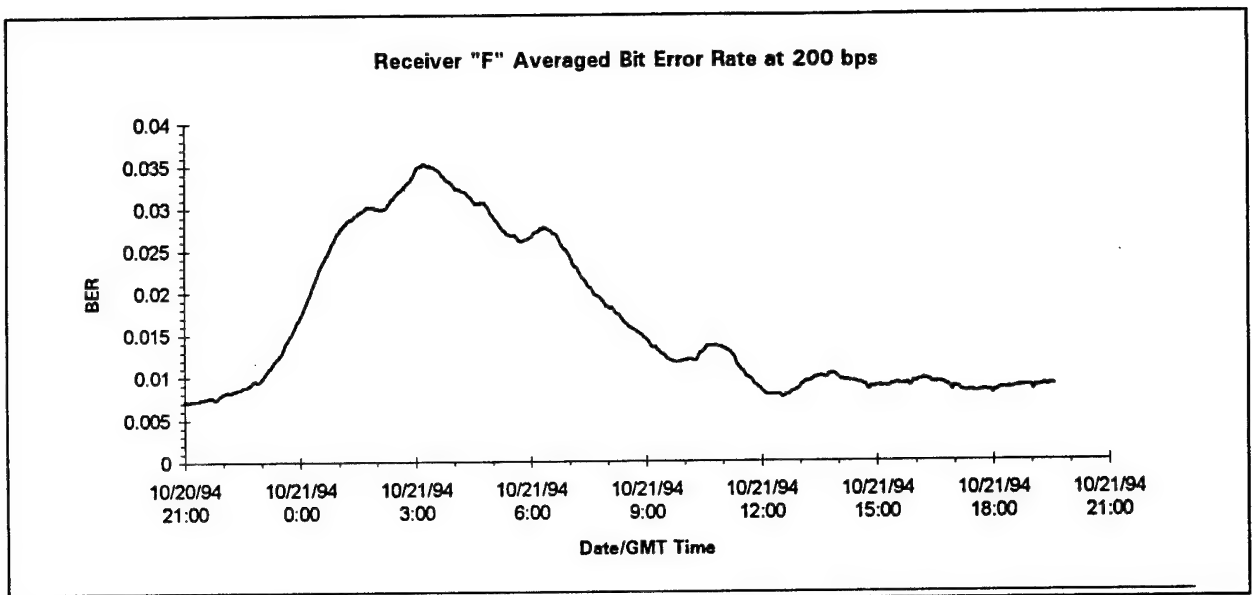


Figure 10 Receiver F Averaged Bit Error Rate at 200 BPS

With this preliminary evidence from the graphs, a set of Analyses of Variance (ANOVA) was performed on the data. ANOVA is a form of hypothesis testing which allows testing for several means. It was used here to determine if there were statistically significant differences in the bit error rates detected between the four different receivers. ANOVAs were performed for the four receivers at both the 100 BPS and 200 BPS levels for each day of the sample. The results concurred with the graphs, and showed a significant difference between the receivers for detected bit error rates.

The next step was to perform numerical analysis on the data. T-tests, a form of hypothesis testing, were used to determine if the differences between data collected from the same receiver type at different transmission rates were statistically significant. The T-test results confirmed the graphical data, in general showing the differences to be statistically significant. On most of the days tested, the receivers performed better at 100 BPS than at 200 BPS. On one of the days, where there was a sustained period of low atmospheric noise followed by a period of high atmospheric noise, the BER graphs for half of the receivers showed no significant difference in performance between the 100 BPS and 200 BPS. It was hypothesized that the sustained period of low noise "swamped" the effects of transmission rate during the higher noise for the calculation of BER averaged over the previous hour. This hypothesis was confirmed when a second set of T-tests was performed for that day, separating the time of high atmospheric noise. Once again, all receivers performed better at 100 BPS than at 200 BPS.

These data provided some insight into how the receivers under test were impacted by high atmospheric noise when receiving data at either 100 BPS or 200 BPS. Additionally, it suggests how these same variables may affect navigational accuracy. The next set of tests were designed to examine this question in greater detail.

Message Type-Navigation Accuracy (MTNA)

In order to determine optimum message types at different data rates, a look-up table comparing correction age versus radial error was required. Once this information was determined, then bit error incident data from the BER tests could be analyzed for intervals between bit hits. These intervals could then be translated into correction ages for the test periods, which would provide information to determine radial error values. The look-up table was obtained from a data graph, which is shown in Figure 11. By collecting large amounts of data with various latency ages, the curves were drawn by fitting empirical data points. The values in the figure represent the 95th percentile, or 95 percent of all of the radial error values are contained by that statistic for the data collected at that correction age.

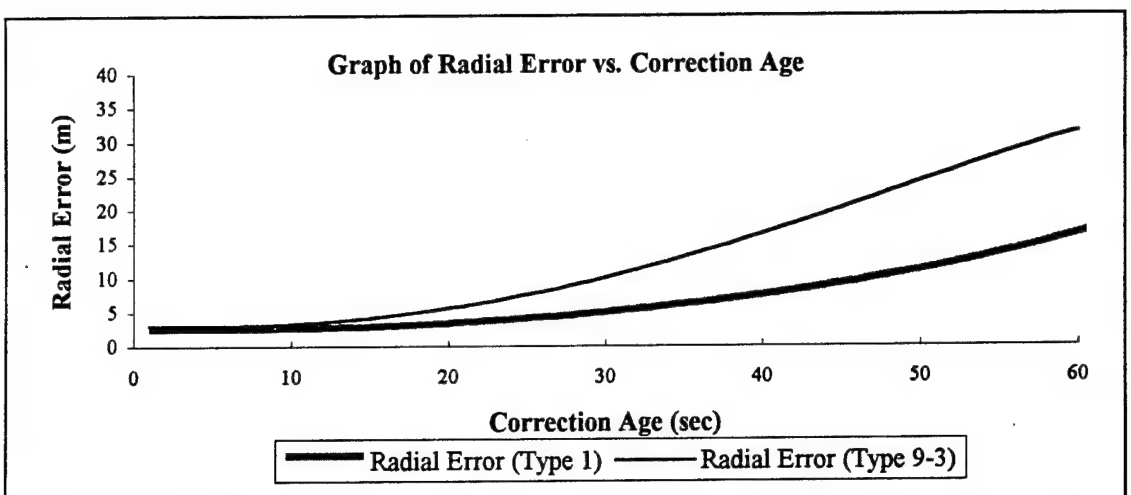


Figure 11 Graph of Radial Error vs. Correction Age

Figure 11 indicates that with increasing time the radial error for message Type 9-3 increases more rapidly than for Type 1. This is what was measured with the equipment used. It does not necessarily

imply that Type 1 messages provide superior performance. In theory, the Type 9 will degrade quicker than the Type 1 due to clock drift in the reference station. The difference in these two curves is directly dependent on this drift rate and how well the reference station is able to characterize it. Caution must be exercised not to make any conclusions at this point from Figure 11 about the optimum message type. This graph is an input to the next step in the process in determining MTNA.

Once the correction age vs. radial error graph was constructed, the next step was to graph the message types at 100 BPS and 200 BPS for each receiver type for each day. The graphs indicated a discernible difference in performance between message types, as well as between transmission rates.

Next, sets of T-tests were run to determine if the differences detected between samples of different broadcast speed (100 vs. 200 BPS) and message type (Type 1 vs. Type 9-3) were statistically significant. The T-test concurred with the preliminary graphical evidence, and showed the differences to be statistically significant.

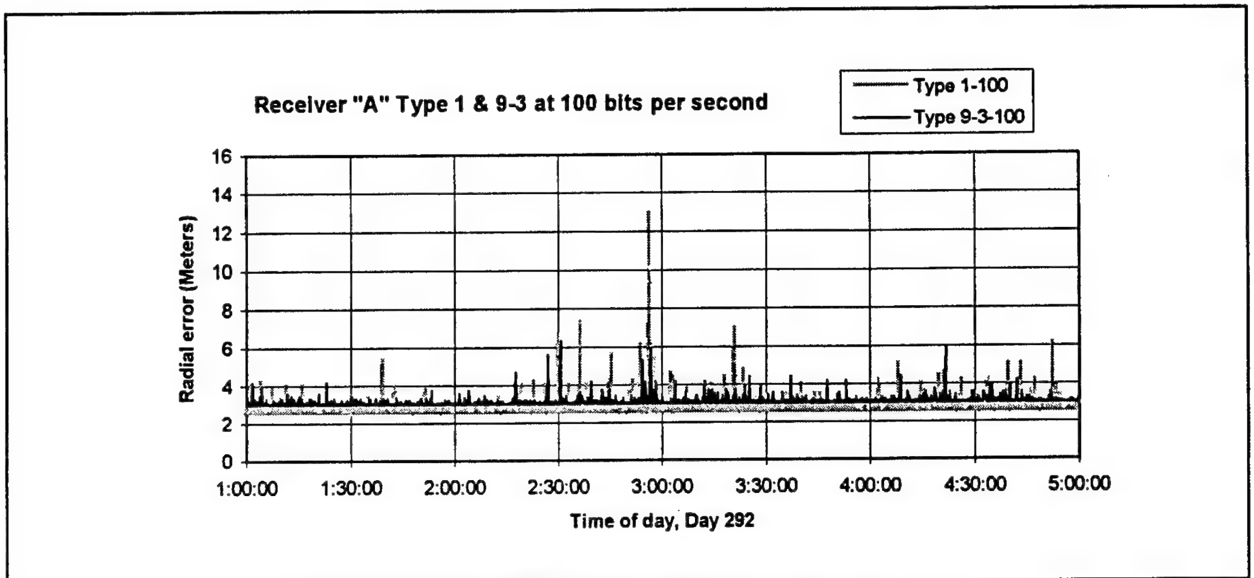


Figure 12 Receiver A Type 1 and Type 9-3 at 100 BPS

Finally, Figure 12 through Figure 23 were constructed to compare radial error over time for specific message types and bit rates. Samples of data from each receiver tested are presented. The time period of 0100-0500 GMT on day 292 was chosen for analysis due to the high atmospheric noise activity. As can be seen in the preceding BER graphs, this period of time was characterized by significant BER values due to relatively high atmospheric noise. The results from each receiver are presented as a sequence of three graphs. Each figure presents two performance curves, one in gray in the background and one in black in the foreground. The series of data assigned to the background was chosen to make the chart more clear. The first figure of each set shows a comparison of radial error over the four hour period for message Type 1 and Type 9-3 at 100 BPS. The second figure compares message Type 1 and Type 9-3 at 200 BPS. The third figure compares message Type 9-3 at 100 and 200 BPS. In every receiver case at 100 BPS, Type 9-3 was the optimal messaging algorithm. In every case at 200 BPS, Type 9-3 was the optimal messaging algorithm. At both 100 and 200 BPS Type 9-3 minimized the degradation in performance due to atmospheric burst noise. The Type 9-3 solutions provided a more

consistent and reliable level of accuracy. In every case Type 9-3 at 200 BPS outperformed Type 9-3 at 100 BPS. In every case Type 9-3 and 200 BPS are shown to give the best performance in the presence of atmospheric noise. It is important to note that the results are not dependent upon the receiver. While the radial error values might be higher for receiver 'F' during this time period because it had higher BER values, Type 9-3 messages still outperformed Type 1 messages for this receiver.

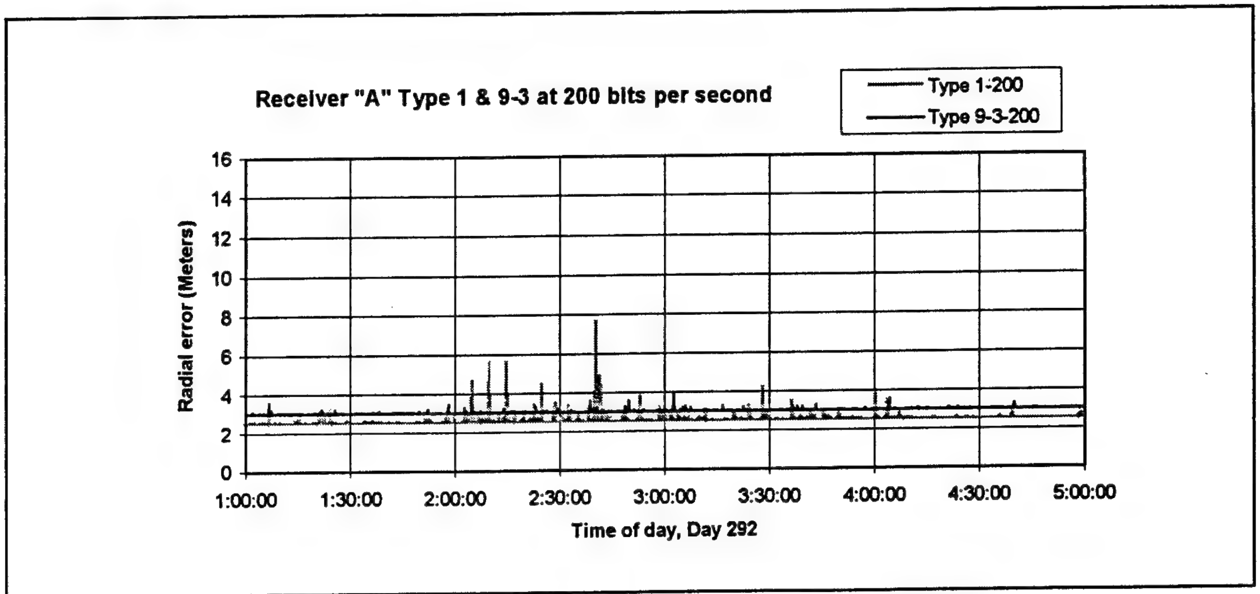


Figure 13 Receiver A Type 1 and Type 9-3 at 200 BPS

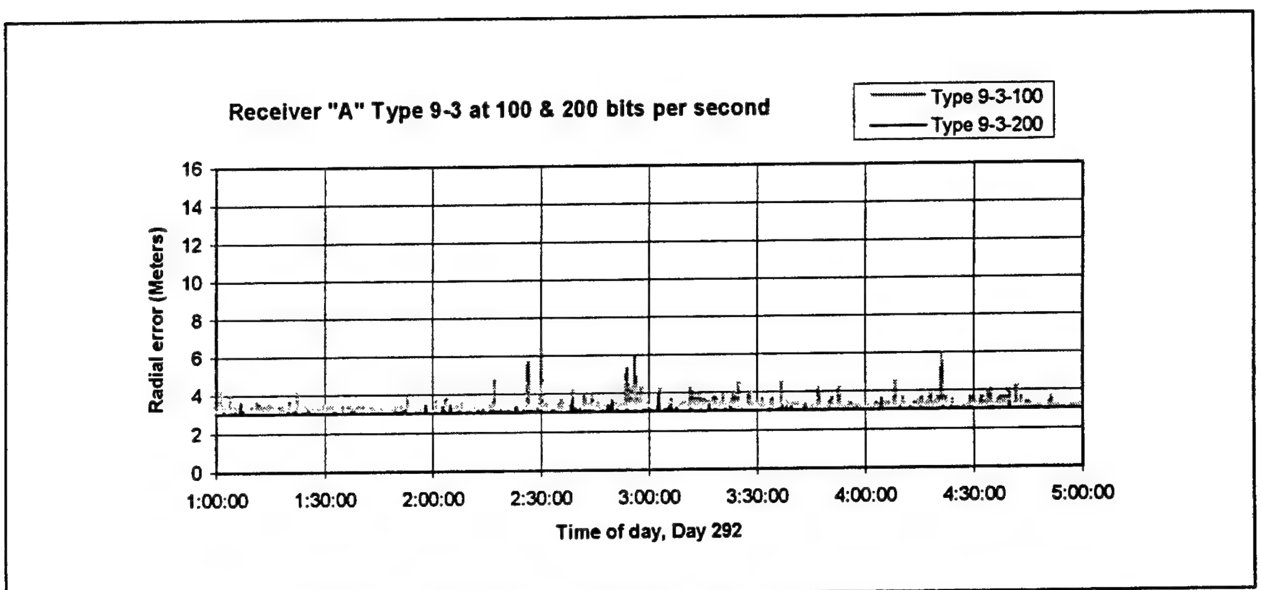


Figure 14 Receiver A Type 9-3 at 100 and 200 BPS

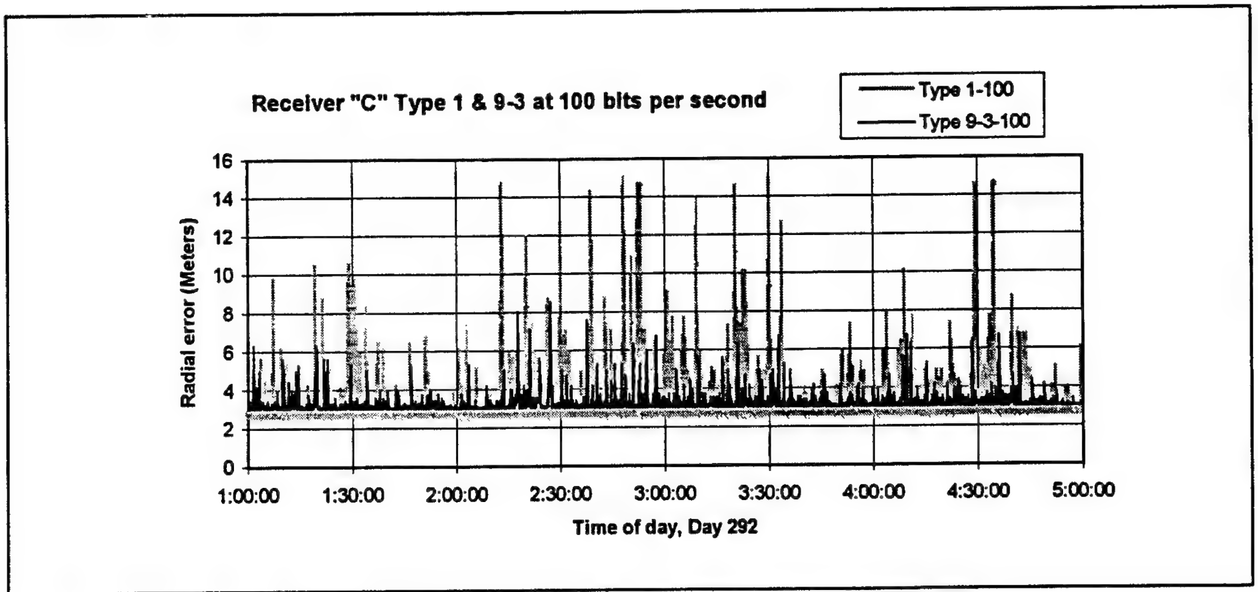


Figure 15 Receiver C Type 1 and Type 9-3 at 100 BPS

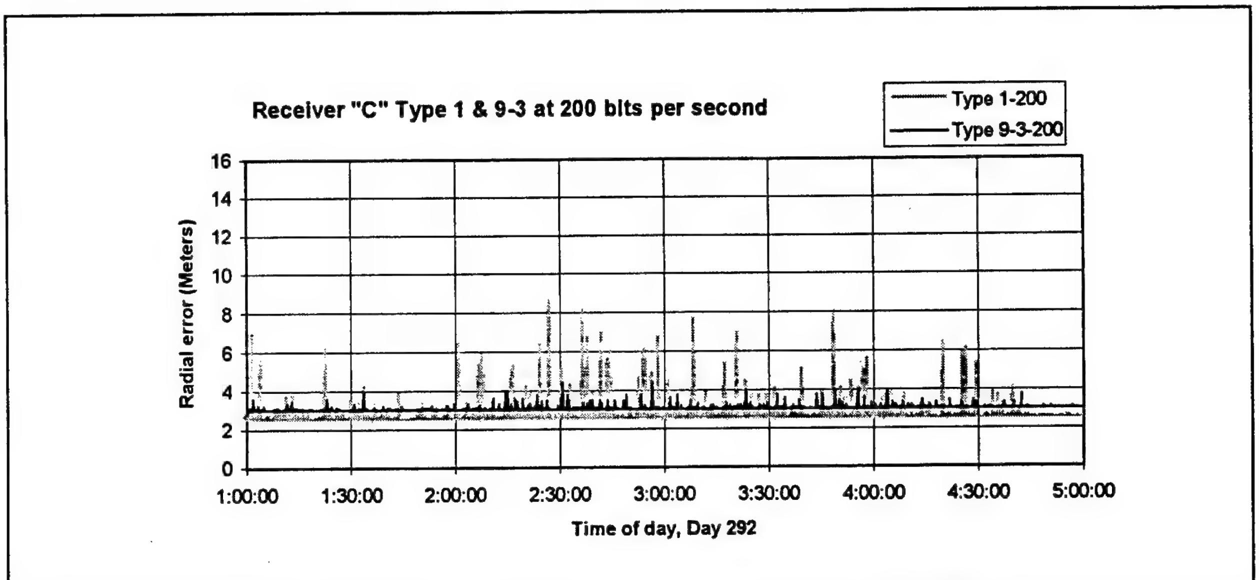


Figure 16 Receiver C Type 1 and Type 9-3 at 200 BPS

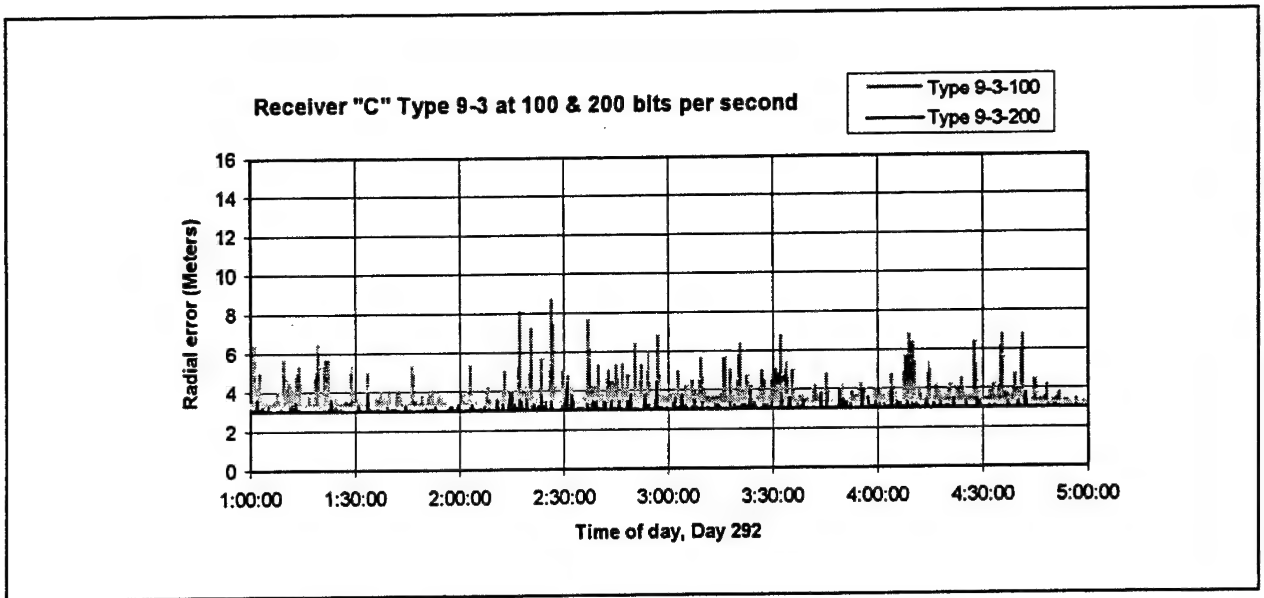


Figure 17 Receiver C Type 9-3 at 100 and 200 BPS

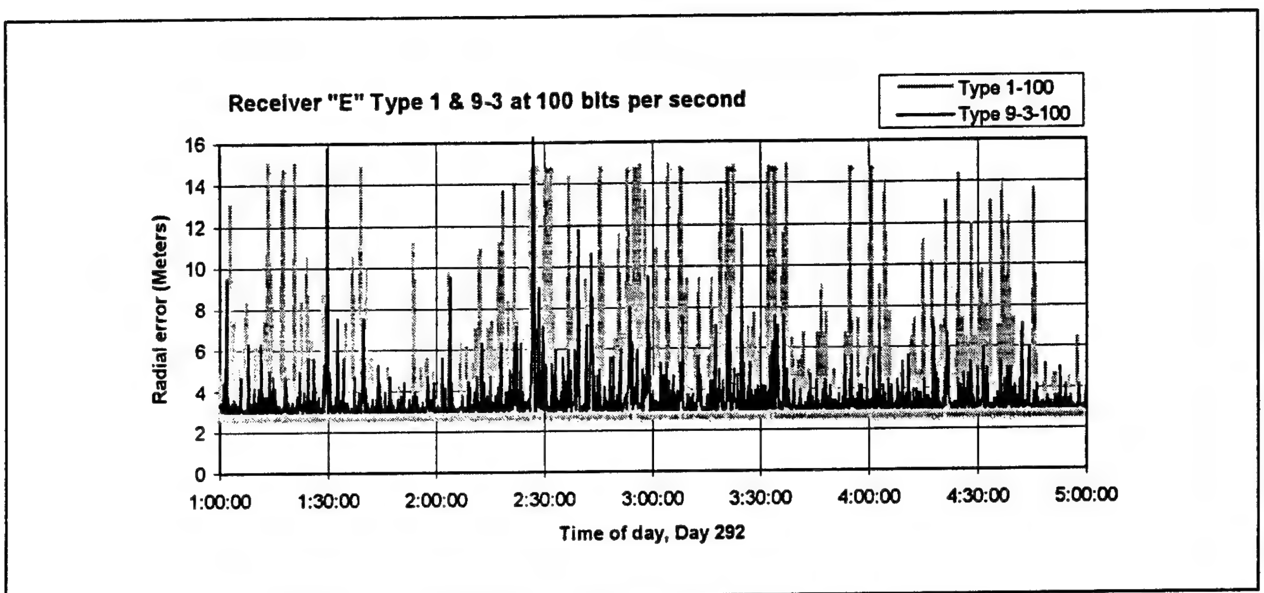


Figure 18 Receiver E Type 1 and Type 9-3 at 100 BPS

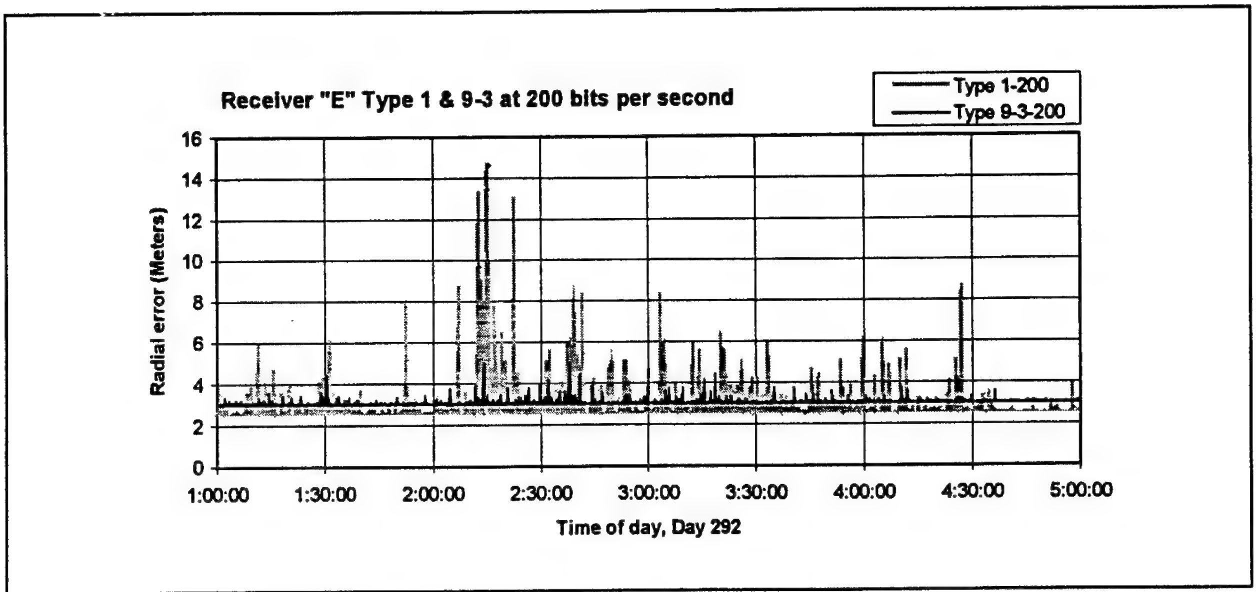


Figure 19 Receiver E Type 1 and Type 9-3 at 200 BPS

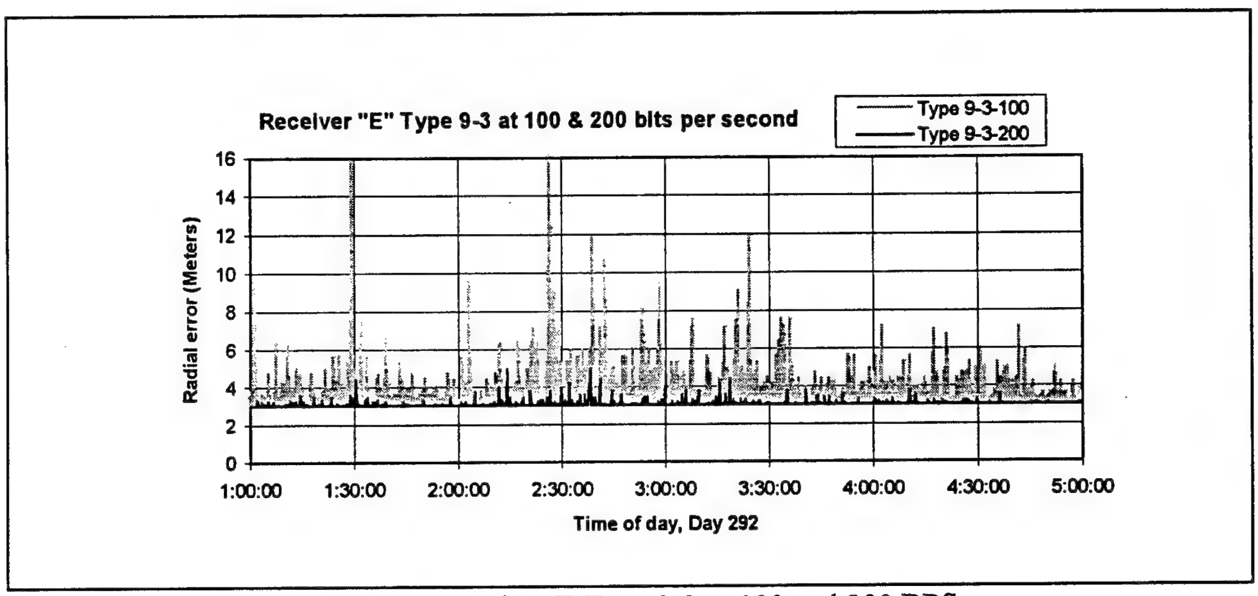


Figure 20 Receiver E Type 9-3 at 100 and 200 BPS

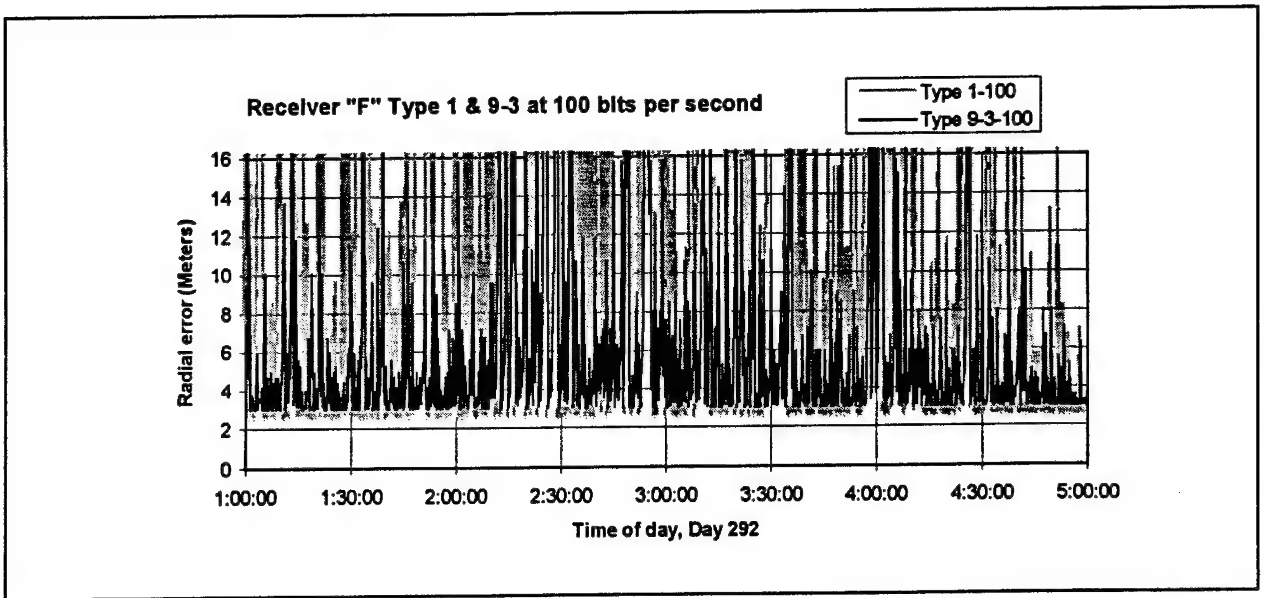


Figure 21 Receiver F Type 1 and Type 9-3 at 100 BPS

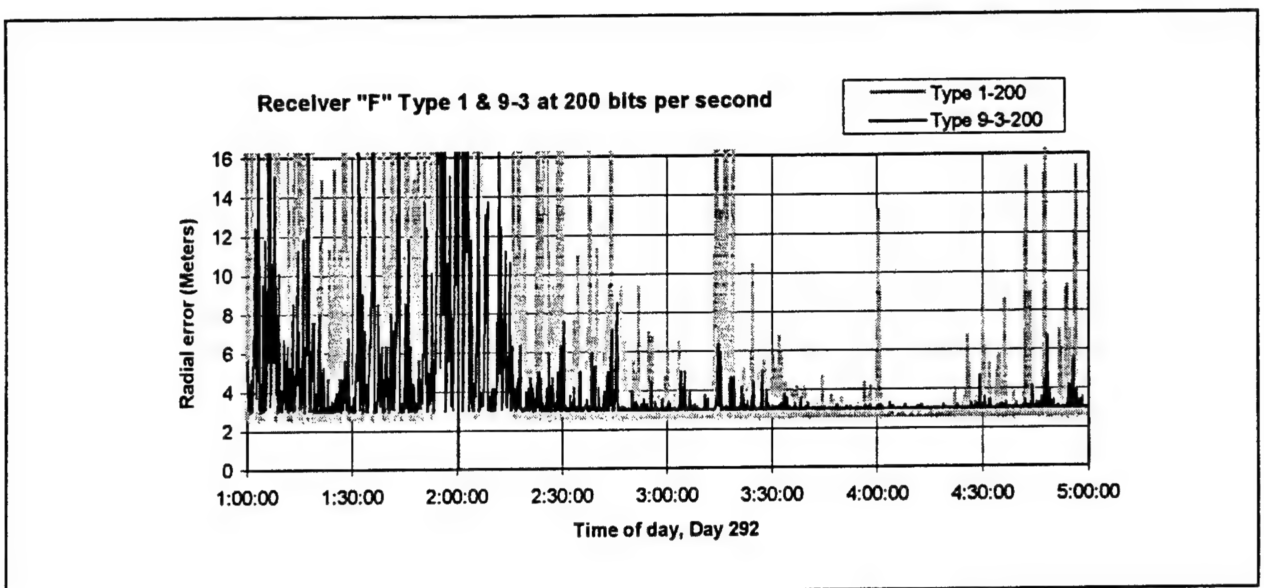


Figure 22 Receiver F Type 1 and Type 9-3 at 200 BPS

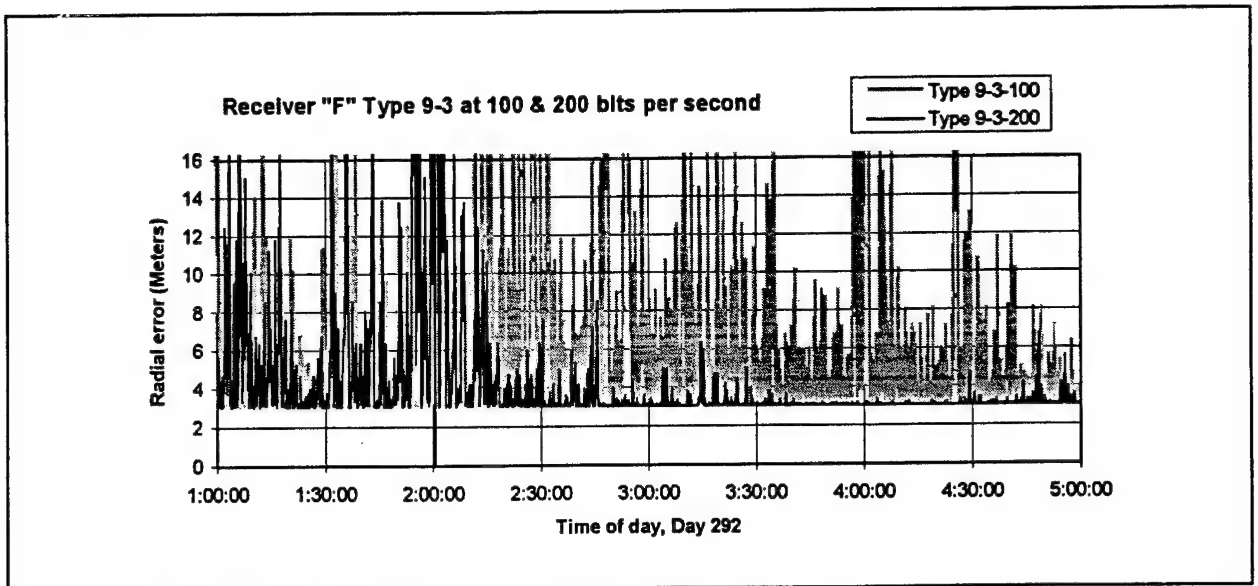


Figure 23 Receiver F Type 9-3 at 100 and 200 BPS

This is interesting, and suggests that all transmissions should be done at 200 BPS using the Type 9-3 method regardless of specified field strength. These tests do confirm the earlier research finding that the optimum message type for DGPS corrections is Type 9-3 at a transmission rate of 200 BPS. Although the results are conclusive in this regard there would be some question regarding performance using actual DGPS transmissions. There is some anecdotal evidence that the use of 100 BPS has allowed operation in areas where 200 BPS on a different day from the same beacon has had problems. Given the many variables that can occur from day to day in this frequency band a test must be designed to allow simultaneous testing of 100 & 200 BPS at equal field strengths of 75 uV/ M.

Interference/jamming (INTJAM)

Five tests were conducted to determine receiver susceptibility to CW signal interference. The specifics of each test are shown in Table 1. All tests used 313.5 kHz as the experiment control (labeled Ctl in Test #), and 316.5 kHz as the experiment test (labeled Int in Test #). The control and test signal strengths remained constant for each test, and varied within a few points of -56 dBm between tests due to varying humidity and rainfall at the testing site. The jammer starting and ending voltages, Start (V) and End (V) in decibel-millivolts (dBm) respectively, were selected to ensure no effects at the start and noticeable effects towards the end of the test.

Table 1 Interfering Frequency Plan

Test #	Int freq	dBm	Ctl freq	dBm	Start V(dBm)	End V(dBm)	Step (dBm)	Start f (kHz)	End f(kHz)	Step (kHz)
1	316.5	-58	313.5	-57.5	-80	-60	2.5	318.000	316.500	0.1
2	316.5	-58	313.5	-57.5	-80	-60	2.5	316.530	316.520	0.001
3	316.5	-54.5	313.5	-54	-80	-60	2.5	316.530	316.520	0.001
4	316.5	-56.8	313.5	-57.1	-72	-51.6	2	316.527	316.523	0.001
5	316.5	-56.8	313.5	-57.1	-72	-51.6	2	316.527	316.523	0.0005

Test #1

Test #1 had the jammer going from 318000 to 316500 Hz. The signal level never exceeded that of the Int MSK signal. This test revealed that the receivers were unaffected by the carrier under these parameters; the interfering frequency has to be very close in order to affect the DGPS MSK signal. This information was used to improve the second test.

Test #2

Under the hypothesis that the MSK signal is most vulnerable to interference at its upper and lower shift frequencies (+/- 25 Hz for a 100 BPS signal, or 316525 Hz and 316475 Hz), the frequency of the interferer was run from 316530 to 316520 Hz, with the interfering signal strength from about -75 dBm to -60 dBm. The MSK signals were at -57.5 dBm, so the jammer had approximately half the power of the desired signal.

The results were inconclusive as there were bit errors occurring in both the control and test frequencies. The interfering signal had no measurable effect as all of the receivers demonstrated similar performance.

Test #3

This test was conducted a day after Test #2, and used the same parameters. The jammer frequency was swept from 316530 to 316525 Hz. The one new factor for this test was that after the sweep was over the interferer was shut down. After 40 minutes of clear reception, the interferer was placed at 316525 Hz at 60 dBm (part 2 of Test #3), the critical frequency with maximum signal level.

The control receivers were unaffected by the interferer. The test receivers performed the same as test #2 for the first part. When the second part of the test was run none of the test receivers were able to maintain lock on the MSK signal. Clearly, a strong signal that is directly on a critical frequency for MSK reception will have a significant impact upon a receiver's ability to demodulate that MSK signal.

Test #4

This test was conducted shortly after Test #3. The jammer frequency varied from 316527 to 316523 Hz, and used time steps of only 10 seconds (Tests #2 & #3 had 30 seconds at each point). The purpose of this test was to attempt to simulate a more rapidly changing interferer.

The control receivers showed some bit errors, probably caused by some other error source. The test receivers showed no degradation.

Test #5

Test #5 was the last test conducted for INTJAM. All receivers displayed almost identical susceptibility to CW jammer interference when the jammer was at least 5 dBm stronger than the MSK signal. Also, the control at 313500 Hz displayed a decreased SNR, even though it was at times more than 3 kHz away from the jammer. This data is shown for receiver F in Figure 24 and Figure 25.

The control at 313500 Hz did not lose any messages during the test. The 316500 Hz signal, however, did suffer catastrophic message losses whenever the jammer reached its peak; in this test, the jammer went from 15 dBm below to 5 dBm above the MSK signal. Clearly, what messages did get through for the 316500 kHz unit (and the count was reduced) were almost all lost. This behavior of message loss was repeated almost exactly the same for all four receivers, with greatest vulnerability shown at jammer frequencies of 316526.0 Hz and 316525.5 kHz. These data indicate that the receivers are susceptible to jamming in the presence of strong signals, even when those signals may be up to 5 Hz away from the critical shift frequency.

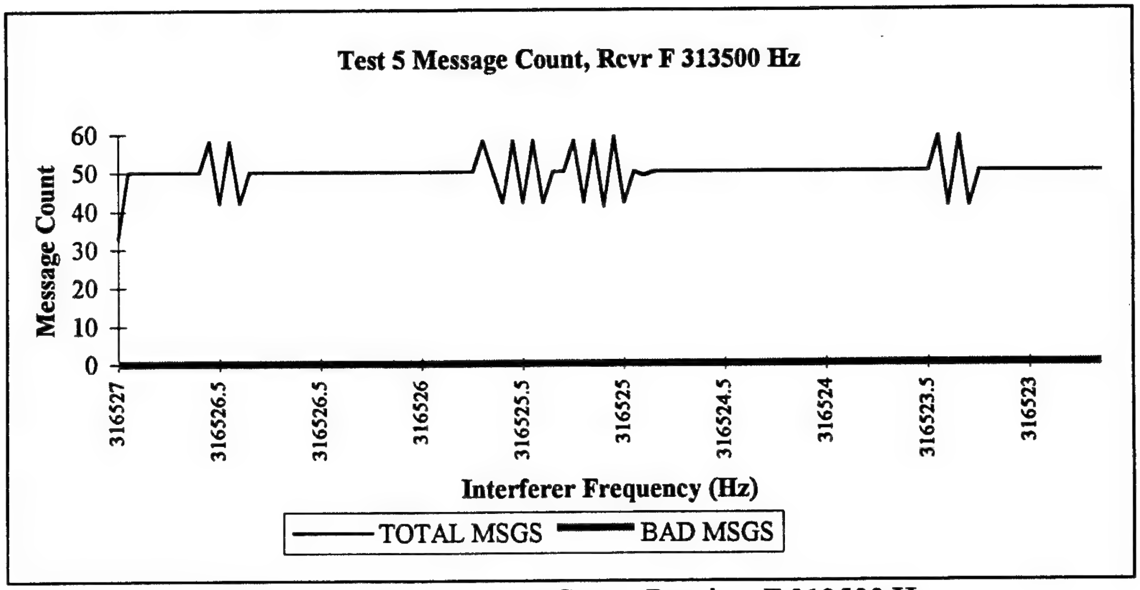


Figure 24 Test 5 Message Count, Receiver F 313500 Hz

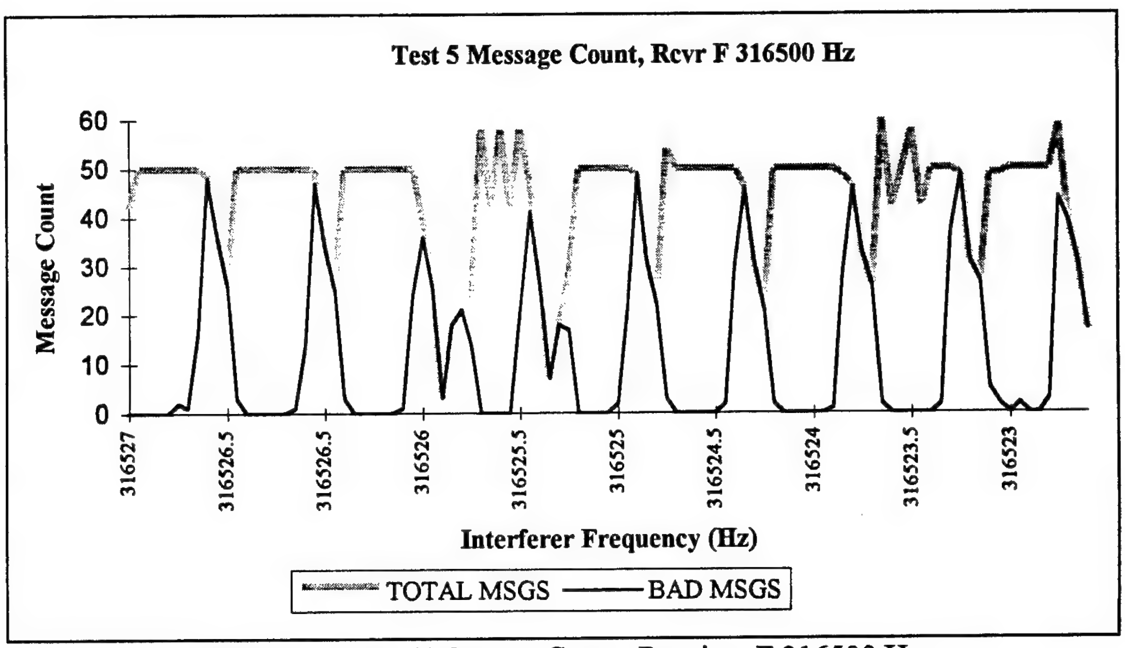


Figure 25 Test 5 Message Count, Receiver F 316500 Hz

There is an interesting phenomenon observed during the testing shown in Figure 26 and Figure 27. These figures compare SNR over time for 316500 Hz and 313500 Hz as the jammer steps through quantized signal levels (LVL DIFF), then progresses through frequency samples. As expected, the SNR was significantly degraded for the 316500 Hz receiver as the average noise level is raised by the interfering signal.

The interesting part is the effect the interfering signal had on the control receiver. Even though the control receiver did not lose any messages, its SNR was also degraded. While the degradation for the control was not as much, it is substantial and would make a difference if the MSK signal at 313.5 kHz was weaker. This behavior was replicated by all receivers, and may be attributable to one of two factors. First, there is the possibility of receiver front-end overload due to the test setup. This is unlikely, given that SNR plots for Tests 1 through 3 showed no decrease in SNR for the receiver at 313.5 kHz, but the receiver at 316.5 kHz did have a degraded SNR as expected. The more plausible explanation is that this is due to a tendency by the receivers to either suffer from adjacent channel interference when the jammer signal is several kHz away or that the jammer signal raised the ambient noise, thus reducing the SNR. In the latter case or rather a case where the sample noise power is not evenly distributed in frequency, the SNR may not be a true indication of the receiver's ability to receive and demodulate data.

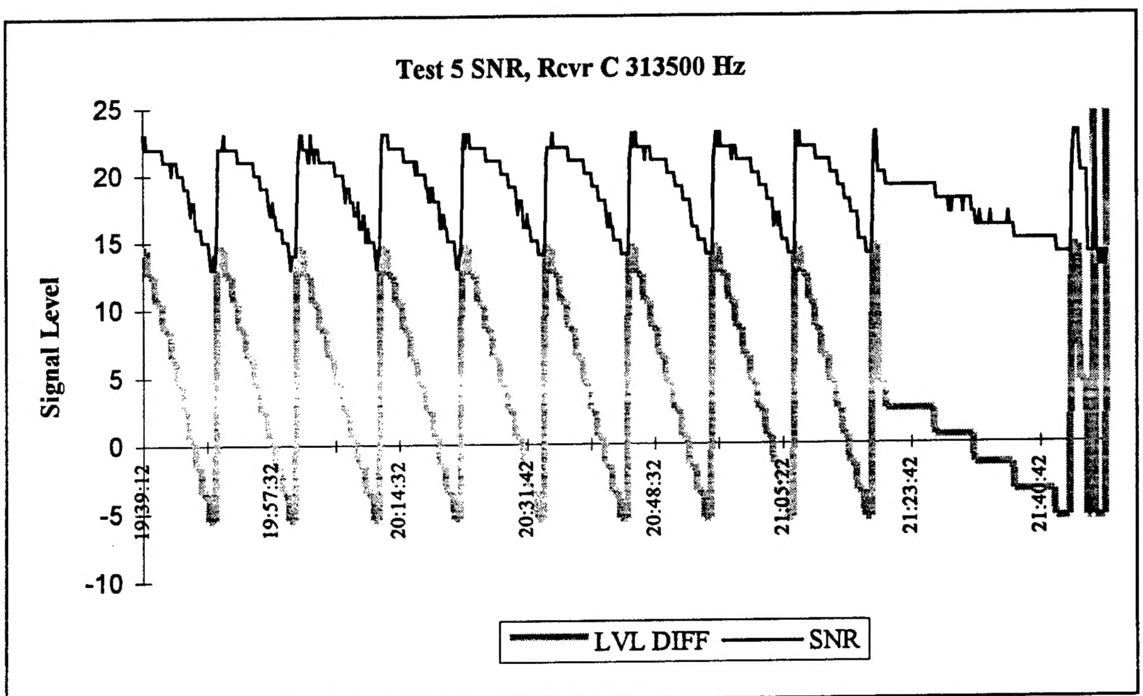


Figure 26 Test 5 SNR, Receiver C 313500 Hz

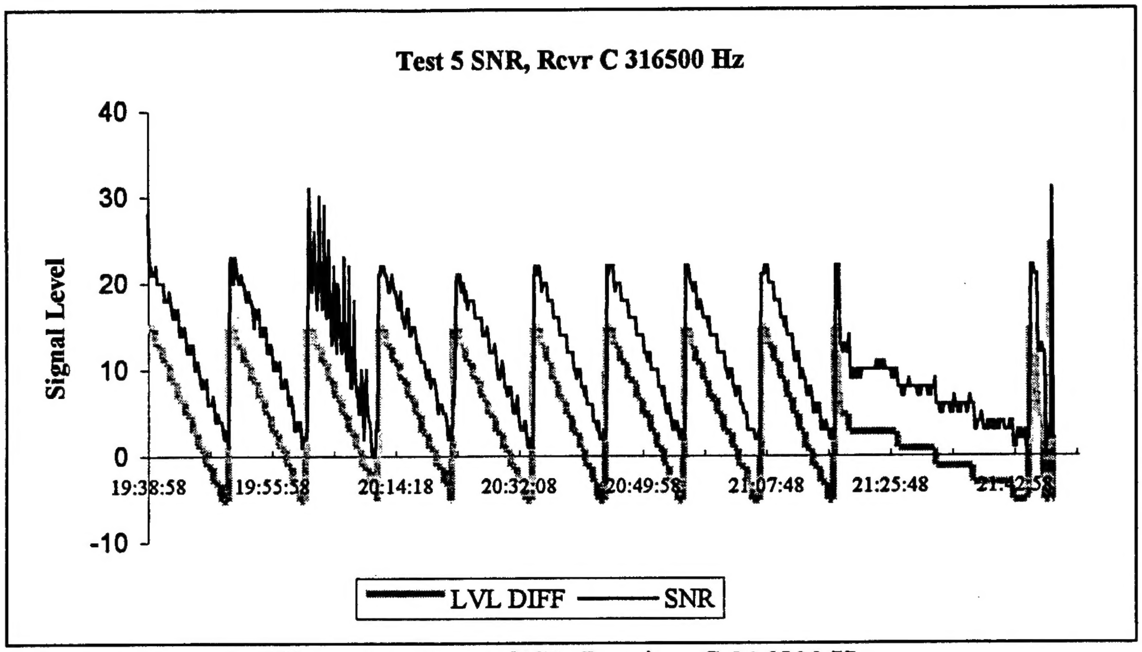


Figure 27 Test 5 SNR, Receiver C 316500 Hz

CONCLUSIONS

The data show that all the tested units can receive MSK signals under the proposed USCG broadcast parameters. In our test configuaration, the testing revealed that some receivers did not have adequate reception during severe storms. It should be noted that these tests were performed using units procured in 1993 and 1994. Although some of these units are still available today, there have been advances in the software and antenna systems presently in use. Most currently available products are generally used with a magnetic field antenna and not the electrical field antennas used in this test. While the results of the testing are still valid, the specific performance of the various receiver systems tested has probably improved.

In the presence of atmospheric noise, message Type 9-3 had an advantage over Type 1 in the presence of atmospheric noise. Furthermore, operating at 200 BPS provided superior performance to 100 BPS transmission. This is interesting, and suggests that all transmissions should be done at 200 BPS using the Type 9-3 method regardless of specified field strength. These tests do confirm the earlier research finding that the optimum message type for DGPS corrections is Type 9-3 at a transmission rate of 200 BPS. Although the results are conclusive in this regard there is some question regarding performance using actual DGPS transmissions. There is some anecdotal evidence that the use of 100 BPS has allowed operation in areas where 200 BPS on a different day from the same beacon has had problems. Given the many variables that can occur from day to day in this frequency band a test must be designed to allow simultaneous testing of 100 and 200 BPS at equal field strengths of 75 uV/ M.

With regard to interference from other CW signals, all receivers demonstrated similar vulnerability. Very strong jammers had an effect upon MSK signal reception, even when the jammer frequency was several kHz away from the MSK frequency.

RECOMMENDATIONS

A full scale test using actual DGPS beacon transmissions should be conducted to verify these tests. The Coast Guard could then consider changing the Type 9-3, 100 BPS broadcasts currently in place to Type 9-3, 200 BPS. The potential for improved availability within the coverage area combined with the simplicity of a single bit rate for the whole system justifies this consideration.

USCG DGPS service availability is currently defined as the percentage of on-air time recorded by the integrity monitor at the radiobeacon transmitter. Occurrences of interference have a significant impact on the availability at the system user without affecting the availability of the service. Refining the Coast Guard DGPS service by moving the availability requirement to reflect what a typical or defined user would experience would make it more customer focused. This type of effort would require a better understanding of the nature and effects of natural and man-made interference in various geographic areas. While the effects of natural occurring interference have been well studied, the problems associated with man-made interference, especially in major ports (urban areas) needs additional work to quantify coverage and navigation performance. Incidents of interference should be collected from the user community. In areas where problems occur, investigations should be made to determine the nature of interference and possible solutions to increase user availability.

As mariners increase their use of DGPS for navigation in harbor and harbor approach areas they will become more dependent on the system. Improvements in the user's availability will enhance the service and create a safer waterways.

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